JOURNAL OF AGRICULTURAL RESEARCH

VOL. 67 WASHINGTON, D. C., AUG. 15, 1943 NO. 4

LIFE HISTORY AND DISTRIBUTION OF PYTHIUM AND RHIZOCTONIA IN RELATION TO DAMPING-OFF OF RED PINE SEEDLINGS[1]

By L. F. ROTH, formerly *research assistant*, and A. J. RIKER, *professor, Department of Plant Pathology, Wisconsin Agricultural Experiment Station*[2]

INTRODUCTION

Damping-off continues to influence production in Wisconsin forest nurseries. Serious outbreaks are sporadic but small losses are experienced each year. The unpredictable occurrence of epidemic attacks in the various nurseries is a handicap to the sustained production demanded by the extensive planting program. Losses are less severe on newly cleared land, but economy is requiring the continued use of land already improved. Results with available control measures on infected land are highly variable, both between different localities in the same year and in the same localities during different years. Various modifications of cultural practices fail consistently to control the disease. The common soil treatment with sulphuric acid, while often successful in controlling damping-off, may both cause toxic injury to the seedlings and produce undesirable disturbances (*20*)[3] in the nutrition and biology of the soil.

The extensive literature of well-known damping-off diseases of conifer seedlings has been reviewed elsewhere, e. g., by Hartley (*7*), C. Roth (*15*), Ten Houten (*18*), and L. F. Roth.[4]

The causal agents described by the various workers have commonly been *Pythium* spp. and *Rhizoctonia solani* Kühn, with species of *Fusarium* and *Phytophthora* active in certain localities. With exceptions noted later, most earlier work has been on etiology and control measures with relatively little attention devoted to epidemiology.

In the present series of studies the basic information essential to intelligent development of control measures for Wisconsin has been sought. This paper deals with the identification of the causal fungi,

[1] Received for publication June 19, 1942.

[2] The writers are indebted to the Wisconsin Conservation Department and to the Bureau of Plant Industry, U. S. Department of Agriculture, for cooperation and encouragement in these investigations; to W. H. Brener, Carl Hartley, F. G. Kilp, and S. A. Wilde both for suggestions and for cooperation during the course of the studies herein reported; to Eugene Herrling for help in preparing the illustrations; and to C. Eisenhart and F. S. Smed for advice and assistance in connection with the analysis of variance and regression analysis and their interpretation. Assistance in making many of the tests was furnished by the personnel of the Work Projects Administration, Official Project No. 65-1-53-2349.

[3] Italic numbers in parentheses refer to Literature Cited, p. 147.

[4] ROTH, L. F. THE INFLUENCE OF ENVIRONMENTAL FACTORS UPON THE DAMPING-OFF DISEASE OF CONIFER SEEDLINGS CAUSED BY PYTHIUM AND RHIZOCTONIA. 1940. [Unpublished doctor's thesis. Copy on file, University of Wisconsin library, Madison, Wis.]

the symptoms they induce, their life histories in relation to pathogenesis, and their distribution. In subsequent papers are considered the influence on damping-off of temperature, moisture, and soil reaction (*16*) and the seasonal development of the disease in the nursery (*17*).

CAUSAL ORGANISMS

ISOLATION

The causal fungi were readily isolated from damped-off seedlings. During the fall of 1936, in the greenhouse, red pine (*Pinus resinosa* Ait.) seed was planted in infected Plainfield sand from the nursery at Wisconsin Rapids. Typical damping-off appeared 3 days after emergence of the first seedlings. A suitable section was removed from the diseased hypocotyl of each damped-off seedling, sterilized for 3 minutes in 1-to-1,000 mercuric chloride, washed twice in sterile water, and plated on potato agar. *Pythium* cultures were purified by subsequent transfers of hyphal tips through water agar. The fungi most commonly obtained were: (1) Phycomycetes, resembling *Pythium*, (2) several species of *Fusarium*, and (3) a few cultures resembling *Rhizoctonia*. The studies on pathogenicity, cultural characters, and morphology were originally made on the 2 dozen cultures thus secured and checked by numerous subsequent isolations.

PATHOGENICITY

The pathogenicity of certain cultures upon red pine was tested in the greenhouse. Four-inch pots of Plainfield sand from the nursery were steamed for 20 minutes at 15 pounds pressure. While still hot, each pot was placed on a clean bench in a section of a sterile Petri dish and was fitted with a cover consisting of a truncated celluloid cone plugged at the top with nonabsorbent cotton. Twenty-four cultures were tested. Four pots were allowed for each culture and 8 pots for controls. For soil inoculation, cultures on potato agar in Petri dishes were cut into 4-mm. squares. Six squares were spaced uniformly on the soil surface of each pot. Control pots received squares of sterile agar. Each pot was seeded with 25 washed red pine seeds placed at the same level as the inoculum. Seed and inoculum were covered three-sixteenths of an inch deep with steamed nursery soil. When necessary, distilled water was added from below. At 3-day intervals after emergence all damped-off seedlings were removed with sterilized forceps, and the number from each set of 4 pots was recorded. The counts were continued for a month, when the seedlings had reached an age of practical immunity. The results are given in table 1.

All cultures of *Pythium* and *Rhizoctonia* were pathogenic on red pine. The *Rhizoctonia* cultures damped-off an average of about 60 percent of the seedlings and ranged from 23 percent (F–3) to 95 percent (F–118). *Pythium* cultures also averaged 60 percent but ranged from 36 (F–10) to 87 (F–111–A) percent. These results correspond with Hartley's (*7*) report that ". . . the variation in virulence between the different strains of *P. debaryanum* on pine seedlings is less than the variation in strains of *Corticium vagum*." Hartley [5] now

[5] Correspondence.

considers that the fungus on which he reported was not *P. debaryanum* and probably was the same as that used in the present studies. The *Fusarium* strains here isolated were apparently of little importance in causing damping-off of red pine. Isolations in every case yielded the fungus used for inoculation.

TABLE 1.—*Pathogenicity of single hyphal tip cultures of damping-off fungi upon red pine in steamed soil*

Fungus	Culture No.	Seedlings emerged from 100 seeds	Damping-off			
			Post-emergence	Pre-emergence [1]	Total	
		Number	*Number*	*Number*	*Number*	*Percent* [2]
Pythium	F–1	52	28	35	63	72
	F–7	63	9	24	33	38
	F–8	46	19	41	60	69
	F–9	70	16	17	33	38
	F–10	78	22	9	31	36
	F–11	66	18	21	39	45
	F–13	48	20	39	59	68
	F–20	55	28	37	65	75
	F–22	73	35	14	49	56
	F–111	60	26	27	53	61
	F–111–A	42	31	45	76	87
	F–117	49	26	38	64	74
Fusarium	1	86	0	1	1	1
	2	[3] 88	0	0	0	0
	3	86	1	1	2	2
	4	[3] 90	2	0	2	2
	5	85	0	1	1	1
	6	87	1	0	1	1
	7	86	0	1	1	1
Rhizoctonia	F–2	51	18	36	54	62
	F–3	78	3	17	20	23
	F–5	57	21	30	51	59
	F–8	62	25	25	51	59
	F–118	23	19	64	83	95
Control	(4)	86	0	----------	0	0
	(4)	88	1	----------	1	1

[1] Numbers represent germination in controls less germination in inoculated pots.
[2] Percentages represent total damping-off in inoculated pots expressed as percentage of seedlings emerging in controls.
[3] Emergence slightly greater than average for the controls may be attributed to variability in germinating capacity of seed.
[4] No inoculation.

IDENTIFICATION

The characteristic vegetative growth and reproductive structures formed on plant tissue in clear agar readily placed the phycomycetous isolates in the genus *Pythium*. Five representative cultures were identified by Charles Drechsler, of the United States Department of Agriculture, as *Pythium irregulare* Buisman. This fungus produces many spherical to pyriform sporangia and later numerous spherical oögonia that in many cases bear several projections of various sizes. Both smooth and irregular oögonia are found on the same thallus. This fungus is obviously closely related to *Pythium debaryanum* Hesse but differs in possessing the occasional oögonial projections. The writers have found no report of *P. irregulare* causing damping-off of conifer seedlings. Buisman (*2*) originally isolated *P. irregulare* from decaying roots of peas and lupines and from cucumber seedlings which failed to emerge. Matthews (*10*) isolated it from a decaying gametophyte of *Anthoceros* and from damped-off tomato plants.

The strains of *Rhizoctonia* represented by cultures F–5 and F–118, and a number of isolates with the same cultural characteristics as F–119 were all isolated from damped-off conifer seedlings grown in Plainfield sand. Culture F–119, however, was obtained from a

sclerotium on a potato tuber grown in Plainfield sand. To corroborate the morphological evidence regarding specific rank of the *Rhizoctonia* cultures, in a single test, the three strains were inoculated into incisions in young potato sprouts and into sterilized soil seeded with cabbage and with red pine. All of the three cultures produced lesions on potato shoots, but only F–118 and F–119 attacked the cabbage seedlings. Cultures F–118 and F–5 caused severe damping-off of pine seedlings while F–119 was not pathogenic. It appeared that the *Rhizoctonia* cultures were strains of *Rhizoctonia solani*.

The morphology of the several isolates of *Rhizoctonia* studied conformed closely to that given by various workers (*14*, *3*, *12*) for strains of *R. solani*. When grown on potato-dextrose agar they fell into three distinct cultural groups: (1) Cultures typified by F–118 appeared distinctly mealy with abundant, short, minutely tufted hyphae. Growth was close to the substrate, and there was a tendency toward zonation. Aerial mycelium was light-colored, the colony appearing drab (*13*). No pigment was formed in the substrate, and no sclerotia were produced. (2) Cultures resembling F–119 appeared silky with long, straight hyphae radiating from the point of inoculation. Tufted mycelium was sparse, zonation lacking, and growth was close to the substrate. The cultures were drab but not so light as F–118. No pigment was formed in the substrate. A true sclerotium 1 to 3 cm. in diameter invariably formed at the point of inoculation, and small sclerotia appeared in contact with the glass at the edge of the Petri dish. All sclerotia were closely appressed to the substrate. (3) Cultures typified by F–5 had, in addition to the radiating surface mycelium, a dense interlacing web of aerial hyphae over the colony. Many dark brown mycelial tufts 0.5 to 2.0 mm. in diameter, made up of short, barrel-shaped cells, were enmeshed in the aerial mycelium and at the surface of the substrate. The culture was distinctly zonate. The mycelium was dark brown, the colony appearing bister (*13*). Some brown pigment was formed in the substrate. Though the above mycelial tufts appeared like sclerotia, they did not become hard or homogeneous like the sclerotia of F–119.

SYMPTOMS CAUSED BY PYTHIUM AND BY RHIZOCTONIA

Characters of moderate diagnostic value are known in relation to the distribution of *Pythium* and *Rhizoctonia* damping-off in the conifer seedbeds, *Pythium* commonly occurring in a roughly random manner, but *Rhizoctonia* appearing in definite fair-sized patches within which most or all seedlings are killed. However, differential symptoms on individual seedlings have not been found by the writers in the several comprehensive descriptions (*9*, *7*, *15*) of conifer damping-off. On Plainfield sand, where *Pythium* and *Rhizoctonia*, respectively, were the fungi concerned, and where the seedlings were examined at suitable stages of development, the writers found that the two fungi produced distinctive symptoms in the same host. Though most observations were on red pine, this condition appeared also for jack (*Pinus banksiana* Lam.), eastern white (*P. strobus* L.), and Austrian (*P. nigra* Arn.) pines.

The following descriptions are based on an examination of seedlings of all ages damped-off (1) in the greenhouse in disease-free soil inoculated with identified pure cultures and in naturally infected soil and

(2) in the nursery in inoculated soil and in naturally infected soil. The seedlings were grown over wide ranges of environmental conditions. The symptoms were checked by isolations of the causal fungi in several hundred cases. The details of these series of studies are omitted because of their volume.

Roots of seedlings less than 2 weeks old were attacked by *Pythium* at any point throughout their length. Older roots became infected in their younger parts. Seedlings from soil containing *Pythium* showed all degrees of infection from lesions bordering on microscopic visibility to a buckthorn-brown (*13*) discoloration of the entire root except the remote tip involving the growing point. This discoloration of the root was the first symptom of *Pythium* damping-off and became more or less complete before the disease appeared above the soil surface (fig. 1, *A*). In contrast to the hypocotyl, which later became infected, roots in the early stages of destruction might be entirely discolored and water-soaked and yet appear firm and distended. They showed no tendency to shrivel, and since the above-ground parts appeared normal, they evidently continued to absorb water.

Infection of the hypocotyl was by growth of the fungus upward through the primary root and therefore was not apparent until relatively late in the course of seedling destruction. The base of the hypocotyl of seedlings attacked by *Pythium* was commonly a shade of green either lighter or darker than the normal plant green. The intensity of this color appeared to be influenced by seedling age and environment. The red pigments completely disappeared from the infected areas but were unchanged in the upper, uninfected parts. During the early stages infected tissues were water-soaked, translucent, and not greatly shrunken. However, even with abundant moisture the advanced lesions became shriveled.

Initial attack by *Rhizoctonia* was most frequent at the base of the hypocotyl or root crown. Within the seedling the fungus advanced more slowly than did *Pythium* and appeared to grow either up or down the main axis with equal facility. Attacked seedlings, therefore, showed typical above-ground damping-off symptoms relatively early in the course of the disease. The lower parts of roots on such seedlings were commonly found to be white and healthy (fig. 1, *C, D*).

Chlorophyll, as well as the red pigment, was destroyed in tissues attacked by *Rhizoctonia*. The red pigments were either formed anew or translocated from their original position in the base of the hypocotyl up to the originally green top. The predominant color of fresh lesions was a dark, bluish gray-green. Lesions on the hypocotyls of seedlings near the age of seed-coat shedding became bleached almost to a straw color. These infected parts then appeared dry and fluted and later became markedly shriveled. Seedlings attacked by *Rhizoctonia* when only the hypocotyl curve extended above the ground were usually olive-green in color and often appeared even a little inflated. Examination of seedlings of all ages attacked by *Rhizoctonia* showed numerous mycelial strands extending from the soil to the seedling. When such seedlings were pulled from the ground, a small quantity of soil was commonly found laced to the stem by the superficial mycelial web.

While symptoms caused by *Pythium* and *Rhizoctonia*, respectively, were distinct, the presence of other damping-off fungi, invasion by secondary organisms, or the lapse of too long a time after infection

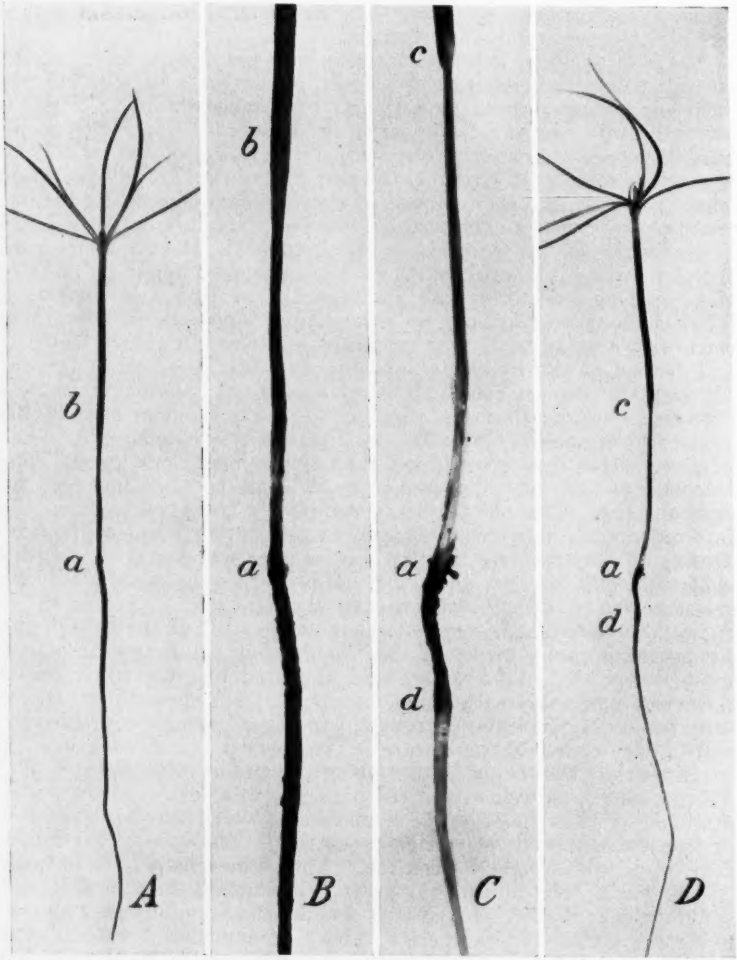

FIGURE 1.—Symptoms caused by *Pythium* (*A* and *B*) and *Rhizoctonia* (*C* and *D*) on 2-week-old red pine seedlings. *B* and *C* are, respectively, 3× enlargements of *A* and *D*. In every case the soil line is at *a*. In the case of *Pythium* (*A* and *B*) all the tissue below *b* is diseased, that from *b* to *a* is water-soaked and dark green, and that below *a* is water-soaked and brown. In the case of *Rhizoctonia* (*C* and *D*) the tissue from *c* to *d* is diseased; that from *a* to *c* is straw-colored, dry, and somewhat shriveled; that from *a* to *d* is brown and has probably been invaded by secondary fungi; that below *d* appears healthy.

could obscure the typical *Pythium* and *Rhizoctonia* symptoms. Therefore, field identification had to be approached with caution.

LIFE HISTORIES IN RELATION TO PATHOGENESIS

Certain phases of the life histories of *Pythium* and *Rhizoctonia* are correlated with the symptoms induced and have been studied on red pine in some detail. The account below is based on both visual and cultural examinations of damping-off foci, of over 100,000 damped-off and associated healthy seedlings in various Wisconsin forest nurseries and on studies made in the greenhouse, where seedlings were grown in naturally and artificially infected soils over a wide range of controlled soil temperature, moisture, and acidity. The details of these trials are omitted because of their volume.

PENETRATION AND PARASITISM

Pythium and *Rhizoctonia* differed in their respective growth habits in relation to the substrate. *Rhizoctonia* appeared only slightly inhibited by low soil moisture and seemed strongly aerobic. *Pythium*, on the other hand, was semiaquatic and capable of growth deep in the soil. The influence of these differences in growth habit and of host resistance on penetration was examined.

The growth of *Rhizoctonia* over the soil surface in very high humidity has been observed by various workers (e. g., C. Roth, *15*) and was found by the writers to be much more rapid than growth within the soil. However, examinations indicated that though the fungus spread rapidly by this means and mycelium frequently enveloped the several-day-old stems, it often failed to penetrate the hypocotyl. Occasionally close mycelial contact produced minute rudimentary lesions, but these did not ordinarily develop to the point of causing damping-off.

This apparent resistance of seedling hypocotyls was tested in the greenhouse with thirty-five 3- to 5-day-old seedlings that were inoculated with 4-mm. blocks of a potato agar culture of *Pythium*. A similar group was inoculated with *Rhizoctonia*. One block was placed against each seedling on a small paper platform three-eighths inch above the soil surface. The inoculation was made in a glass chamber in the greenhouse at 24° C. and approximately saturated humidity.

The results showed that *Rhizoctonia* mycelium quickly surrounded the hypocotyls, occasionally formed incipient lesions, but failed to develop further. The mycelium frequently grew down into the soil. Two days later seedlings began to damp off and continued until 93 percent were destroyed. *Pythium* attacked the seedlings directly at the point of inoculation, destroying 17 percent before it entered and attacked from the soil. Six days were required after inoculation before attack by *Pythium* through the soil became general. Eventually it killed all seedlings. Apparently the hypocotyl was highly resistant to *Rhizoctonia* and moderately resistant to *Pythium*. Root tissues remained susceptible.

Examination of seedlings in the nursery and in the greenhouse, when they were grown under controlled conditions, indicated that *Rhizoctonia*, when growing above the ground, could attack seedlings just emerging. Many seedlings around the margins of damping-off foci and with only their curved hypocotyls protruding from the

ground were found damped-off. Frequently an enlarging lesion was found at the top of the curve, while parts adjacent to and under the ground were healthy. The evidence that attack was by aerial or surface mycelium confirmed similar observations by C. Roth (*15*). Apparently hypocotyls of very young seedlings were susceptible to aerial mycelium of *Rhizoctonia*, but they quickly gained resistance. The upper root and crown remained susceptible for a longer period. However, the cotyledons remained susceptible long after the hypocotyls had acquired resistance. Thus aerial *Rhizoctonia* mycelium may cause much damage through this means of entrance—and even through the needles of 2- or 3-year-old trees.

The growth of *Pythium* occurred at various depths within the soil. It appeared above the soil surface only under very humid conditions when growing over dead tissues. Its attack was largely confined to the roots. The point of infection appeared to be determined by the age of the tissues, the moisture content of the soil, and thus by the depth of the fungus in the soil. If the soil was quite wet, the infection was commonly close to the surface; if dry, the lesions appeared at deeper levels.

The longer susceptibility of seedlings to *Pythium* than to *Rhizoctonia*, reported by C. Roth (*15*), was confirmed by the writers. It appeared to result from differences in growth habit of the two fungi, correlated with tissue maturity of the host. For example, the older parts of the seedling (i.e., hypocotyl, crown, and upper root) first became resistant. *Rhizoctonia*, because it developed most profusely in the surface layers of soil or superficially over the soil surface, was early confronted by these maturing tissues, where its effectiveness as a pathogen was limited. However, *Pythium* could grow in the soil to depths equaling those normally attained by the roots of red pine seedlings during their first summer. Below the levels where *Rhizoctonia* was highly active and in a region accessible to *Pythium*, susceptible root tissue was being continuously produced. These roots were readily attacked by *Pythium*. Seedlings more than 6 weeks old showed typical root rot rather than damping-off.

Mechanical Injury and Fungus Penetration

Mechanical injury to conifer seedlings has influenced damping-off. C. Roth (*15*) and Arnold Hansson [6] found various arthropods associated with seedling hypocotyl injury at the soil surface. Wilde (*19*) reported soil nematodes in healthy seedlings as possibly important in opening infection courts for damping-off fungi. The writers observed in various Wisconsin nurseries that seedlings decapitated by birds appeared to damp off more severely than uninjured seedlings. While some seedlings were killed directly by such treatment, the survivors commonly had injuries that seemed not only to open infection courts but also to weaken the seedlings, making them more susceptible to damping-off.

The influence of two types of injury on susceptibility was studied experimentally in the greenhouse. Three hundred 3- to 7-day-old red pine seedlings were pierced at the base of the hypocotyl and root crown with approximately 35 minute holes made with insect micropins having a diameter of about 0.1 mm. Immediately after injury

[6] Correspondence.

the seedlings in groups of 25 were transplanted into twelve 4-inch pots of Plainfield sand, 4 of which had been inoculated at their surface with *Pythium* F–111–A, 4 with *Rhizoctonia* F–5, and 4 left uninoculated as controls. Two other groups of 300 seedlings each were transplanted into 2 similar sets of 12 pots. Immediately after transplanting, the cotyledons of all seedlings in 1 group were clipped just above the terminal bud. The 300 uninjured seedlings of the third group served as controls. Incubation was at 24° C. The humidity was rather low, and consequently little damping-off of uninjured seedlings occurred. Counts were made at appropriate intervals. The losses are recorded in table 2. From this summary table it is evident that piercing alone so severely injured the seedlings that many died as a direct result of the injury. Piercing, moreover, facilitated fungus action. Losses in the *Rhizoctonia* and *Pythium* pots of pierced seedlings exceeded those in the controls by 50 and 53 percent, respectively. Clipped seedlings were much more severely attacked by *Pythium* (25 percent) than those not so injured (2 percent), but losses were not so great as in seedlings with the hypocotyl punctures (91 percent). Clipping had no discernible effect on the injury by *Rhizoctonia*. Some damping-off occurred in both clipped (6 percent) and unclipped (8 percent) seedlings. In all cases this was much less than in the pierced seedlings (94 percent). No damping-off occurred in the controls.

TABLE 2.—*Influence of seedling injury on damping-off of red pine by Pythium and Rhizoctonia*

Treatment	Seedlings killed in soils, according to inoculation [1]		
	Rhizoctonia	*Pythium*	Uninoculated
	Percent	*Percent*	*Percent*
Pierced seedlings	94	91	44
Clipped seedlings	6	25	0
Uninjured seedlings	8	2	0

[1] Values based on 100 transplanted seedlings. Records were taken 2 weeks after treating and transplanting.

The above experiment had four replications of the nine treatments. Results from the different replications were consistent and showed that minute mechanical injuries to the base of the hypocotyl in the presence of the fungi greatly increased damping-off. The injury from clipping the cotyledons had no effect on susceptibility to *Rhizoctonia* but considerably increased that to *Pythium*. The results corresponded with the nursery observation that bird injury increases damping-off.

LOCATION WITHIN THE HOST

The fungi were not limited in their location within seedlings which had developed only a small amount of secondary mechanical tissue. During the early stages of disease development, their location within the host was closely correlated with the point of original infection. In general, they were distributed as shown in figure 1. During later stages, when humidity and soil moisture were favorable, they grew throughout the seedling. With further seedling maturity the fungi became more closely restricted to the point of original infection.

Whole and dissected lactophenol mounts of 3- to 10-day-old seedlings stained with cotton blue showed either fungus to be generally present in the cells of all parenchymatous tissues of the lower hypocotyl and upper root. Only rarely, however, was mycelium found in the secondary vascular elements or woody tissues. Oögonia and sporangia of *Pythium* occurred infrequently in the host tissues. However, when infected seedlings were allowed to stand in water for 12 to 48 hours, both of these structures were formed abundantly in the surrounding medium.

EXIT FROM THE HOST

The two fungi grew freely from the diseased tissue back into the soil (*6*). Their continued saprophytic development was apparently enhanced by the nutrient supply furnished by the dead seedlings.

DISSEMINATION TO THE NEW HOST

The common means of localized spread from one host to the next was direct growth through the soil. The character of this growth differed for the two fungi. *Pythium* was usually well distributed in the seedbeds and spread, though slightly, down the drills. *Rhizoctonia* commonly radiated as much as a foot or two from an original infection point, spreading both along and across rows and killing irregularly circular patches of seedlings.

For dissemination from one nursery block to another, the fungi appeared commonly to be carried in contaminated soil by instruments, water, and wind. The capacity of *Rhizoctonia* to survive in dust is discussed in a later section.

LONGEVITY AND OVERWINTERING

The overwintering of fungi causing damping-off of conifers and their longevity in the soil have been rather obscure. On other hosts—for example, on rice—*Rhizoctonia* has been observed by Palo (*11*) to live from season to season in the sclerotial stage. Buried sclerotia lost their viability after 4 to 5 months in wet soil and 6 to 7 months in dry soil. Sclerotia on the soil surface lived for 5 and 7 months, respectively, in wet and dry soils. Gratz (*5*) found that after 6 months in soil dried down at high greenhouse temperatures *Rhizoctonia* caused as severe damping-off of cabbage seedlings as occurred in the soil before drying.

The longevity of conifer damping-off fungi was studied in various field trials, the data for which have been omitted because of their volume and because the inadequate control over conditions allowed possible error. In general, the trials indicated that both *Pythium* and *Rhizoctonia* could live for more than a year.

The survival of damping-off fungi in Wisconsin has been studied under controlled conditions. The soil used was virgin Plainfield sand from a jack pine woods near Wisconsin Rapids. When a sample was seeded to red pine in the greenhouse under conditions favorable for damping-off, it was found entirely free from *Pythium* and *Rhizoctonia*. Two lots of soil were inoculated with pure whole-oat cultures of *Pythium* and *Rhizoctonia*, respectively. After the fungi had become established, the soil was passed through sterilized screens to remove

the oats, placed in sterilized glazed jars, and seeded to red pine. Throughout the experiment, which was begun in the fall, every precaution was taken to avoid contamination; i. e., the soil was handled on a sterilized table with sterile instruments, the jars were tightly covered with nonmoistureproof cellophane, and all watering was with distilled water. Severe damping-off occurred in all jars. Isolations from damped-off seedlings, yielding only the fungi which had been introduced, indicated that no contamination occurred. A third lot of naturally infected nursery soil was planted in the same way. It contained about equal amounts of *Pythium* and *Rhizoctonia*. After damping-off was complete, the three lots of soil were allowed to dry to 10 percent of their moisture-holding capacity.

The *Pythium* soil was placed in 240 sterile 6-ounce bottles, 160 gm. of soil per bottle. Half of these were maintained at approximately 10-percent saturation while the remaining 120 were brought to 60-percent saturation with sterile distilled water. The bottles were closed tightly with screw caps to prevent contamination and evaporation. Half of the bottles in each moisture group were packed in sand with their necks protruding and placed out of doors. The remaining bottles were stored in the laboratory. Laboratory temperatures fluctuated around 20° C. while those in the field changed with the seasons. During the winter months the soil samples in the field were frozen solid. The *Rhizoctonia* and naturally infected soils were treated similarly. The 3 lots of infected soil, each having 2 different moistures and being stored at 2 different temperatures, provided 12 different sets of bottles (table 3). There were 60 bottles in each set, or 720 in all.

TABLE 3.—*Damping-off values used for analysis of variance and correlation coefficients with corresponding mean values for testing significance of differences between any 2 locations, any 2 test dates, or any 2 organisms*

Organism	Moisture content	Locations [1]	Damped-off seedlings from 210 seeds planted after inoculated soil had stood for the number of weeks specified										Means	
			8	11	14	17	20	23	28	36	49	55	Locations [2]	Organisms [3]
	Pct.		*No.*	*No.*	*No.*	*No.*	*No.*	*No.*	*No.*	*No.*	*No.*	*No.*		
Natural	10	Field	31	60	52	42	10	84	39	78	64	28	49	46
		Laboratory	42	31	51	43	4	25	21	35	12	14	28	
	60	Field	49	60	80	65	22	59	22	75	1	66	50	
		Laboratory	79	67	74	46	2	89	26	69	93	37	58	
Mean [4]			50	55	64	49	10	64	27	64	43	36		
Pythium	10	Field	54	81	85	70	0	70	36	5	33	55	49	47
		Laboratory	49	74	85	39	0	27	4	15	48	45	39	
	60	Field	46	26	72	62	10	96	57	40	80	86	58	
		Laboratory	23	36	95	52	1	84	41	28	72	11	44	
Mean [4]			43	54	84	56	3	69	34	22	58	49		
Rhizoctonia	10	Field	25	15	38	36	17	72	41	1	42	65	35	32
		Laboratory	36	44	69	21	32	64	19	13	25	0	32	
	60	Field	51	66	66	64	28	14	41	4	41	0	38	
		Laboratory	12	37	25	18	7	25	5	69	18	5	22	
Mean [4]			31	41	50	35	21	44	27	22	32	18		

[1] Places of storage for containers and soil samples during the course of the experiment.
[2] Minimum significant difference (at the 5-percent level) between any 2 location means = 19.59.
[3] Minimum significant difference (at the 5-percent level) between any 2 organism means = 9.79.
[4] Minimum significant difference (at the 5-percent level) between any 2 test-date means = 30.97.

To test the activity of the fungi on each date at various intervals following inoculation seventy-eight 4-inch pots of autoclaved Plainfield sand were placed on a clean greenhouse bench. One section of a sterilized Petri dish was used under each pot to provide for subirrigation. Duplicate bottles of soil from each treatment were employed in the test and their contents used to cover the 35 seeds in each of 6 pots. There were thus 6 replicates representing each location for each moisture content of each of the 3 infection types, or 72 pots in all. Seed in the 6 remaining pots was covered with autoclaved soil and served as controls. After seeding, each pot was covered with a truncated celluloid cone, the top of which was plugged with cotton. Seedlings were counted 5, 10, and 15 days after emergence. Total damping-off and survival were recorded at each count for the 6 pots. After the third count these values were summed and from them were calculated total emergence, and preemergence and postemergence damping-off. The amounts of postemergence and preemergence damping-off, though not the same, were of the same order. Consequently, only the former were used in presenting the results. These figures for 10 different test dates from March 1939 to March 1940 are given in table 3 with the mean damping-off values calculated for the different test dates, locations, and inoculations, respectively.

Viability tests extended over the period from December 1938 to March 1940. Those made during the first 2 months showed no differences in viability or activity of the fungi and have, for convenience, been omitted from the analysis.

The statistical significance of the amount of damping-off in the three inoculation series with different moistures and with different locations was determined by analysis of variance. This analysis is given in table 4.

TABLE 4.—*Analysis of variance for the number of red pine seedlings damped-off in pots inoculated with soil samples containing Pythium, Rhizoctonia, and naturally contaminated soil*[1]

Variation due to—	Degrees of freedom	Sum of squares	Mean square	F[2]
Organisms	2	6,006.46	3,003.23	6.24**
Moistures	1	1,197.01	1,197.01	2.49
Locations	1	2,475.21	2,475.21	5.15*
Test dates	9	25,959.74	2,884.42	6.00**
Twentieth week vs. others	1	12,546.07	12,546.07	26.09**
Between others	8	13,413.67	1,676.71	3.49**
Organisms × moistures	2	1,950.87	975.43	2.03
Organisms × locations	2	145.87	72.93	.15
Organisms × dates	18	9,191.54	510.64	1.06
Moistures × locations	1	161.00	161.00	.33
Moistures × dates	9	1,483.41	164.82	.34
Locations × dates	9	3,669.21	407.69	.85
Error	65	31,261.67	480.95	
Totals	119	83,501.99		

[1] The various samples had been exposed to different environments for periods ranging from 8 to 55 weeks.
[2] * = Significant at the 5-percent level; ** = significant at the 1-percent level.

Since the mean square corresponding to differences between organisms exceeded the error mean square to an extent statistically significant at the 1-percent level the existence of real organism differences

as regards damping-off may be inferred with small risk—the probability of differences between organisms as large as or larger than those observed occurring through chance fluctuations alone being less than 1 in 100.

Statistically significant differences were found also between locations (at the 5-percent level) and between test dates (at the 1-percent level). One conspicuous feature in table 3 is the fact that the damping-off values for the twentieth week are considerably out of line with the values obtained in the other weeks. Therefore, in table 4 the variation due to the comparison of the twentieth week with the others has been isolated, and it may be noted that the sum of squares for this single degree of freedom is nearly as large as the sum of squares for the 8 degrees of freedom corresponding to the eight independent comparisons between the other nine test dates. The mean square corresponding to the comparison among the other test dates is significant at the 1-percent level, showing the existence of differences between test dates as regards damping-off even when the anomalous data for the twentieth week is disregarded. No statistical significant differences between moistures were detected, nor were any of the first-order interactions statistically significant. This latter finding implies that such differences as existed were consistent throughout; e. g., differences between organisms were independent of location.

The nature of the differences for those factors showing statistical significance may be determined by comparing the differences of means given in table 3 with the corresponding 5-percent minimum significant differences included as footnotes to table 3.

Thus it is apparent that losses from *Rhizoctonia* soil were significantly less than from *Pythium* soil or from naturally infected soil.

The fungi were significantly more active when stored in the field than in the laboratory, except *Rhizoctonia* at 10-percent moisture and those in natural soil at 60-percent moisture.

Discarding the anomalous data for the twentieth week, linear regressions of damping-off means on test dates were calculated for the respective organisms, and the regression coefficients obtained were −.3334, −.2775, and −.4092 for naturally infected and *Pythium*- and *Rhizoctonia*-inoculated soils, respectively. The regression coefficients do not differ from zero to a statistically significant extent when considered alone, but they are statistically significant at the 5-percent level when considered collectively, suggesting that there may be a tendency for activity to decrease. With *Pythium* the deviations from linearity, significant at the 5-percent level, suggest that the decline in activity, if existent, is not linear.

Nevertheless, damping-off fungi survived well over a year. Differences in soil moisture did not influence longevity during the time studied. Considering such longevity in the soil, the wide distribution of damping-off fungi and the prolonged infection of nursery soils is not surprising.

OCCURRENCE AND DISTRIBUTION

The distribution of damping-off fungi seems important because of (1) its bearing on nursery establishment and practice, (2) its possible relation to the natural distribution (*21*) and reproduction of pine species, and (3) the relation these species may have to root rot after transplanting.

Damping-off fungi have apparently been long established in Wisconsin since the disease had appeared by 1913 at Trout Lake (*8*). A 25-percent loss occurred in 1933 in the first seeding at the Griffith State Nursery on land reclaimed from an abandoned field. The first crop at the Gordon State Nursery on land where heavy sod was broken also was severely attacked.

The occurrence of the fungi in Wisconsin has been determined by the damping-off induced and by subsequent isolations from damped-off seedlings. Numerous isolations were made during the summers of 1937, 1938, and 1939 from seedlings damped-off in 6 nurseries in northern and central Wisconsin and in several nonnursery sites. Before plating, ¼-inch sections of hypocotyl, including both incipient infection and healthy tissue, were washed in clear water with a camel's-hair brush, then rinsed vigorously in 2 changes of sterile water, and placed on Petri plates of water agar. Damping-off fungi were readily differentiated after a few days.

The results are first considered in connection with the reaction of the soil from the locations examined.

THE INFLUENCE OF ACIDITY

Soil reaction was studied in relation to the occurrence of damping-off in sandy soils. In table 5 the isolation results, arranged according to acidity, show that in soils more alkaline than pH 5.85 *Pythium* was isolated more frequently than *Rhizoctonia*. The samples for the pH readings were taken from the top inch of soil. In soils more acid than pH 5.85, however, *Rhizoctonia* was almost always more common. Higher *Pythium* damping-off was correlated with acidities less than pH 5.85, giving a coefficient of −.6035. This value is highly significant, according to Fisher's table of r, where, with 20 degrees of freedom, a coefficient of −.413 is required for significance at the 5-percent point. The figures in table 5, representing partial percentage values of the same total, show that *Rhizoctonia* was correlated with acidities greater than pH 5.85. Although the division point between the 2 fungi seems quite sharp at pH 5.85, this point may doubtless be raised or lowered somewhat under other conditions, especially those of weather.

The results indicated that with the soils studied *Pythium* was favored by neutral or slightly acid soils while *Rhizoctonia* predominated on the very acid soils. This relationship has been confirmed in greenhouse and nursery studies (*16, 17*). It is noteworthy that occurrence of the disease due to 1 fungus or the other was not restricted by soil reaction over the range examined.

THE INFLUENCE OF WEATHER

Weather often has appeared to influence the occurrence of damping-off and probably the distribution of the fungi as well. This subject is so important that it is given detailed consideration elsewhere (*16, 17*), and attention is directed here to the influence of different kinds of soil.

TABLE 5.—*Distribution of Pythium and Rhizoctonia in Wisconsin forest nurseries* [1]

Location near—	Soil		Seedlings plated	Platings positive for *Pythium* and *Rhizoctonia*	Yield of positive platings			
	Type	Reaction [2]			*Pythium*		*Rhizoctonia*	
		pH	*Number*	*Number*	*Number*	*Percent*	*Number*	*Percent*
Rhinelander	Vilas sand	[3] 4.98	8	[4] 1	0	0	1	100
Port Edwards	Plainfield sand	[5] 4.98	56	54	0	0	54	100
Do	do	[5] 5.15	82	81	15	18	66	81
Gordon	do	[5] 5.16	13	7	0	0	7	100
Madison	Silt loam	5.26	17	15	3	20	12	80
Trout Lake [6]	Vilas sand	5.35	19	10	8	80	2	20
Wisconsin Rapids	Plainfield sand	5.39	16	16	0	0	16	100
Hayward	do	[5] 5.43	6	2	0	0	2	100
Trout Lake [7]	Vilas sand	5.53	25	18	9	50	9	50
Port Edwards	Plainfield sand	5.75	5	5	0	0	5	100
Do	do	5.82	57	52	0	0	52	100
Do	do	5.84	30	30	7	23	23	77
Do	do	5.84	17	17	0	0	17	100
Do	do	5.84	16	16	3	19	13	81
Rhinelander	Vilas sand	5.88	7	4	3	75	1	25
Hayward	Plainfield sand	5.93	13	11	11	100	0	0
Gordon	do	6.08	40	15	15	100	0	0
Trout Lake	Vilas sand	6.22	17	15	13	87	2	13
Do	do	6.42	51	51	51	100	0	0
Port Edwards	Plainfield sand	6.55	22	22	6	27	16	73
Trout Lake	Vilas sand	6.55	28	19	19	100	0	0

[1] The table is arranged according to soil reaction progressing from high to low acidity.
[2] Determinations were made with a quinhydrone electrode and checked with a glass electrode.
[3] Spring-seeded red pine treated at seeding with 2-percent sulphuric acid to control damping-off.
[4] Plates not giving either *Pythium* or *Rhizoctonia* were either negative or showed saprophytes or dubious parasites.
[5] Fall-seeded red pine treated at seeding with 2-percent sulphuric acid to control damping-off.
[6] Woods soil not in nursery.
[7] Field soil not in nursery.

THE INFLUENCE OF SOIL TYPE

The relative amounts of damping-off were studied in abandoned field soils and in soils with forest cover. Five 4- by 4-foot seed beds were planted and protected from birds and rodents in the spring of 1938 on Plainfield sand at each of three sites. These were: (1) A nursery block used for experimental studies during 1937 and inoculated at that time with damping-off fungi, (2) a field abandoned for 11 years, and (3) a small opening in a middle-aged stand of jack pine with an oak brush understory. The two latter locations were 5 rods apart and differed only in the type of cover and such factors as light and moisture arising from the cover differences. Undoubtedly, the microbiology of these soils also differed. In the nursery the soil contained a moderate amount of organic matter and had a reaction of pH 5.5. In the field soil organic matter was low, the pH was 5.4, and the vegetation was a sparse stand of weeds and bunchgrass. In the woods organic matter was relatively high, the pH 5.8, and the conspicuous ground cover lowbush blueberry and bunchgrass. The beds were spaded thoroughly and half of each was inoculated with one-third quart of a whole-oat culture of *Pythium* and a similar amount of *Rhizoctonia*. The beds were seeded to red pine, and after emergence a record was kept of the number of seedlings damped-off and surviving in all plots. At about 30 days after the seedlings had attained relative immunity, all the tiny trees were pulled and observations made on their development. This procedure was followed three successive times. No additional inoculation was employed in the second and third seedings. Except for a diminution of the

effect of inoculation, the results of the later seedings were in agreement with those of the first.

Damping-off results from the five replications of the first seeding are given only in summary form. In the uninoculated plots in nursery, field, and woods, 9, 15, and 1 percent, respectively, of the emerged seedlings damped off, whereas in the inoculated plots on the same sites the losses were 33, 25, and 14 percent, respectively. All attempts failed to isolate either *Pythium* or *Rhizoctonia* from seedlings damped-off in the uninoculated woods plots while both fungi were isolated with ease from all other situations. The 14-percent loss in inoculated plots in the woods and the 1-percent loss from the uninoculated plots suggested that damping-off fungi were very scarce, if present at all, in the woods before inoculation. Damping-off declined in the inoculated woods plots with subsequent seeding. In the spring seeding of 1939, though a very small amount of damping-off occurred in the inoculated plots of the preceding year, it was no longer possible to isolate *Pythium* or *Rhizoctonia* from the seedlings. Damping-off fungi seemed unable to compete successfully with the organisms already in the woods soil. These results accorded with experience at the Griffith State Nursery, where damping-off was invariably much worse on old field soil than in newly cleared forest soil. Thus it appeared that damping-off fungi may be practically or entirely absent from certain Wisconsin forest soils, but that in abandoned field soils of the same type they may build up to levels as great as those found in contaminated nurseries.

A somewhat similar experiment to determine the influence of site on occurrence of the fungi and disease was conducted in the summer of 1939 at the University of Wisconsin arboretum. The following three locations were chosen: (1) An eroded and exposed sandy knoll in an abandoned orchard having heavy bluegrass sod and a soil reaction of pH 5.4, (2) another sandy knoll with a middle-aged stand of black locust and oak and a pH of 5.3, and (3) a plot covered by a pure stand of oak and having a heavy mull soil with a strongly acid reaction of pH 4.2.

Twelve circular wire covers 15 inches in diameter were placed on each site to keep out birds and mice (fig. 2). In order that conditions of light and soil moisture might be more nearly comparable on all sites, a cheesecloth cover was attached to the square of metal screen covering those beds located in the exposed orchard site. Among the 12 beds on each site were randomized 4 replications of each of the following treatments: (1) one-sixth pint of a corn meal-sand culture of *Pythium* and an equal amount of *Rhizoctonia* mixed into the upper 2 inches of soil at the time of seeding; (2) one-third pint of a sterile corn meal-sand mixture introduced into the upper 2 inches of soil; and (3) no treatment. Two hundred red pine seeds were spread over the smoothed surface of each bed and covered with one-fourth inch of autoclaved potting sand. Damped-off and surviving seedlings were counted and recorded at appropriate intervals after emergence. Damped-off seedlings were plated and, where possible, the causal fungi determined as given in table 6. The plots were seeded and results taken three successive times, the only significant difference in result being a small decrease in damping-off in the second and third seedings of the inoculated plots. The results of the first seeding are given in table 6.

FIGURE 2.—A representative unit of field plots employed in studying the occurrence of damping-off in various natural environments. Each covered plot was sprinkled with white sand just before photographing.

TABLE 6.—*Damping-off of red pine on 3 natural sites in the arboretum, Madison, Wis., and the respective importance of the 2 fungi causing the loss*

Site	Treatment	Seedlings counted				Fungi isolated			
		Germinated		Damped-off		*Pythium*		*Rhizoctonia*	
		Number	*Percent* [1]	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*
Sandy, exposed, pH 5.4.	Inoculated corn meal and sand	216	29	42	19	2	50	2	50
	Sterile corn meal and sand	485	66	29	6	(2)	------	(2)	------
	No treatment	568	78	17	3	(2)	------	(2)	------
Sandy, locust cover, pH 5.3.	Inoculated corn meal and sand	161	22	82	51	2	15	11	85
	Sterile corn meal and sand	514	70	84	16	2	33	4	67
	No treatment	522	71	54	10	1	11	8	89
Mull, oakcover, pH 4.2.	Inoculated corn meal and sand	83	11	49	59	12	60	8	40
	Sterile corn meal and sand	349	48	33	9	8	80	2	20
	No treatment	402	56	66	16	9	82	2	18

[1] These figures are based upon 728 viable seeds as determined by germination tests.
[2] All platings made of the small number of seedlings damped-off in the plots treated with sterile corn meal and sand and the untreated plots on the sandy site were negative for *Pythium* and *Rhizoctonia*.

Some damping-off occurred in the uninoculated beds on all sites. Inoculation, however, in all cases greatly increased the amount. Corn meal and sand alone appeared not significantly to influence the amount of damping-off. Mean losses in the uninoculated beds (sterile corn meal and sand and no treatment) for the three locations, sandy exposed, sandy woods, and mull woods, respectively, were 4.4, 13.3, and 13.2 percent. Comparable losses for the inoculated beds were 19.4, 51.0, and 59.0. The losses on sandy and mull soils in the woods were approximately equal for the inoculated and uninoculated beds and suggested that damping-off fungi occur naturally in both types of soil. The fact that damping-off on the exposed site was

much less severe than in the woods was probably due to less favorable humidity and soil moisture rather than to other differences caused by the shade. Germination was retarded because of dry soil, and after emergence moisture was inadequate until the seedlings had passed the stage of practical susceptibility. These results indicate that in southern Wisconsin damping-off fungi may be equally abundant in both light and heavy, deciduous-wooded soils.

The differences of soil type largely determined which of the two important damping-off fungi would predominate (table 6). In the heavy soil of untreated plots *Pythium* predominated, causing 82 percent of the total loss, while in the sandy soil *Rhizoctonia* was more abundant, causing 89 percent of the loss. These results accorded with Hartley's observation (*7*) that soils high in humus favored *Pythium* while *Rhizoctonia* was more abundant in soils low in humus.

In heavy acid soils the results accorded with those of Gäumann (*4*) and Buchholtz (*1*) obtained with seedlings on similar soils. However, in controlled studies with Plainfield sand (table 5) *Pythium* responded quite differently to soil reaction. This subject is considered further elsewhere (*16*).

DISCUSSION

Variations in the success of control measures applied in Wisconsin against damping-off among forest seedlings and, more particularly, the desire to eliminate empirical drastic treatments that ruin soil fertility have called for more information concerning the disease. The causal fungi have been identified as *Pythium* and *Rhizoctonia*—two organisms that are active not only elsewhere in the United States (*7*) but also in Europe (*15*). Other organisms reported to cause damping-off have been found either not at all or so infrequently as not to be significant.

Since there are two causal agents, the damping-off problem is most clearly defined as dealing with two separate diseases. The dual nature of the situation appears in several respects. The symptoms caused by these two fungi, respectively, when operating alone, are distinct and seem correlated with their growth habits. Likewise, in spite of the striking similarity of the two causal agents, certain observed variations in their mode of attack, dissemination, and longevity are conspicuous. Their distribution in Wisconsin is widespread, but the predominance of one over the other is clearly influenced both by weather and by soil type and acidity.

For an improved understanding of the situation, a detailed examination of the influence of environment on host, parasite, and disease was requisite. The results of such studies are reported elsewhere (*16*, *17*).

SUMMARY

Pythium irregulare and *Rhizoctonia solani* have been found the most destructive of the fungi that cause damping-off of *Pinus resinosa* in Wisconsin forest nurseries. Though species of *Fusarium* were isolated, they occurred in conjunction with the other fungi and in inoculation tests were only slightly, or not at all pathogenic.

Differential symptoms were induced by *Pythium* and *Rhizoctonia*, respectively, when each was free from complicating mixtures with other organisms. The symptoms described appeared correlated with the respective growth habits of the two fungi. *Pythium* attack occurred

at various depths in the soil and was determined by root maturity and the location of the fungus. For the most part, *Rhizoctonia* attack was confined to the upper one-half inch of soil and to saturated air immediately above the soil.

Seedlings with elongating hypocotyls were subject throughout to attack by aerial mycelium of *Rhizoctonia*. After elongation had ceased, however, it appeared that the cotyledons and the primary shoot were the susceptible parts above ground.

Seedling injury, within limits, increased damage from damping-off.

The life history in relation to pathogenesis of these two fungi seemed relatively simple. Both lived in the soil and invaded injured seedlings more easily than uninjured seedlings. They grew through the cortical tissue of living seedlings, all through dead tissue, and out into the soil again. Distribution locally was by growth through the soil, and at a distance, by means of contaminated soil or other material. *Rhizoctonia* survived well in soil containing only 10 percent of moisture and dry enough to blow as dust.

Both *Pythium* and *Rhizoctonia* were capable of surviving more than a year in sandy soil.

In six Wisconsin nurseries and several nonnursery sites examined, one fungus or both were commonly found. Their occurrence was influenced by soil reaction, weather, soil type, and ground cover. Plainfield sand with jack pine (*Pinus banksiana*) or jack oak (*Quercus ellipsoidalis*) cover was associated with the presence of little or none of the damping-off.

The apparently strong influence of acidity, temperature, and moisture called for a detailed study of these factors in relation to damping-off.

LITERATURE CITED

(1) Buchholtz, W. F.
1938. Factors influencing the pathogenicity of Pythium de Baryanum on sugar beet seedlings. Phytopathology 28: 448–475, illus.

(2) Buisman, C. J.
1927. Root rots caused by phycomycetes. Phytopath. Lab. "Willie Commelin Scholten," Meded. 11: 1–51, illus.

(3) Duggar, B. M.
1915. Rhizoctonia crocorum (Pers.) DC. and R. solani Kühn (Corticium vagum B. & C.), with notes on other species. Mo. Bot. Gard. Ann. 2: 403–458, illus.

(4) Gäumann, E.
1928. Über die Bekämpfung des Würzelbrandes der Zuckerrüben. Landw. Jahrb. der Schweiz 42: 571–582, illus.

(5) Gratz, L. O.
1925. Wire stem of cabbage. N. Y. (Cornell) Agr. Expt. Sta. Mem. 85, 60 pp., illus.

(6) Gravatt, A. R.
1931. Germination loss of coniferous seeds due to parasites. Jour. Agr. Res. 42: 71–92, illus.

(7) Hartley, C.
1921. Damping-off in forest nurseries. U. S. Dept. Agr. Bul. 934, 99 pp., illus.

(8) ——— and Merrill, T. C.
1914. Preliminary tests of disinfectants in controlling damping-off in various nursery soils. Phytopathology 4: [89]–92.

(9) ———, Merrill, T. C., and Rhoads, A. S.
1918. Seedling diseases of conifers. Jour. Agr. Res. 15: 521–558, illus.

(10) MATTHEWS, V. D.
1931. STUDIES ON THE GENUS PYTHIUM. 136 pp., illus. Chapel Hill, N. C.
(11) PALO, M. A.
1926. RHIZOCTONIA DISEASE OF RICE: I. A STUDY OF THE DISEASE AND OF THE INFLUENCE OF CERTAIN CONDITIONS UPON THE VIABILITY OF THE SCLEROTIAL BODIES OF THE CAUSAL FUNGUS. Philippine Agr. 15: 361–375, illus.
(12) PELTIER, G. L.
1916. PARASITIC RHIZOCTONIAS IN AMERICA. Ill. Agr. Expt. Sta. Bul. 189: 283–390, illus.
(13) RIDGWAY, R.
1912. COLOR STANDARDS AND COLOR NOMENCLATURE. 43 pp., illus. Washington, D. C.
(14) ROLFS, F. M.
1904. POTATO FAILURES. A SECOND REPORT. Colo. Agr. Expt. Sta. Bul. 91, 33 pp., illus.
(15) ROTH, C.
1935. UNTERSUCHUNGEN ÜBER DEN WURZELBRAND DER FICHTE (PICEA EXCELSA LINK). Phytopath. Ztschr. 8: 1–110, illus.
(16) ROTH, L. F., and RIKER, A. J.
1943. INFLUENCE OF TEMPERATURE, MOISTURE, AND SOIL REACTION ON THE DAMPING-OFF OF RED PINE SEEDLINGS BY PYTHIUM AND RHIZOCTONIA. Jour. Agr. Res. (In press.)
(17) ——— and RIKER, A. J.
1943. SEASONAL DEVELOPMENT IN THE NURSERY OF DAMPING-OFF OF RED PINE SEEDLINGS, CAUSED BY PYTHIUM AND RHIZOCTONIA. Jour. Agr. Res. (In press.)
(18) TEN HOUTEN, J. G.
1939. KEIMPLANTENZIEKTEN VAN CONIFEREN. 128 pp., illus. Utrecht and Amsterdam.
(19) WILDE, S. A.
1936. SOIL NEMATODES IN FOREST NURSERIES. (Phytopath. Note) Phytopathology 26: 198–199, illus.
(20) ———
1937. RECENT FINDINGS PERTAINING TO THE USE OF SULFURIC ACID FOR THE CONTROL OF DAMPING-OFF DISEASE. Jour. Forestry 35: 1106–1110.
(21) ——— and WHITE, D. P.
1939. DAMPING-OFF AS A FACTOR IN THE NATURAL DISTRIBUTION OF PINE SPECIES. Phytopathology 29: 367–369, illus.

SOLAR RADIATION AND FOREST FUEL MOISTURE[1]

By George M. Byram, *associate meteorologist*, and George M. Jemison, *senior silviculturist, Appalachian Forest Experiment Station, Forest Service, United States Department of Agriculture*

INTRODUCTION

A major contribution to progress in forest fire prevention and control during the past 10 years has been the development and widespread application of methods of rating forest fire danger.[2] Fire danger rating systems are now in use in all the forest regions of the United States. They have been described by Gisborne (*8*, *9*),[3] Brown and Davis (*2*), Curry et al. (*4*), Matthews (*13*), Jemison,[4] and others. Under each of these systems the major factors affecting fire danger are measured and the measurements are integrated by means of charts, tables, or some mechanical device into ratings, on a numerical scale, which are free from the serious errors common in estimates of fire danger based on personal judgment alone. The numerical ratings are usually defined in terms of probable fire behavior or of manpower required for suppression. They serve as a guide to efficient distribution of fire-control funds and personnel.

All these fire-danger rating systems include measurement of wind velocity and of fuel moisture content. Wind velocity, an extremely important factor whenever fuels are dry enough to burn, is usually measured with standard instruments. Fuel moisture content is more difficult to determine, because of the complex nature of fuels. Lightweight materials such as fallen leaves, needles, and twigs and dead grass respond readily to changes in atmospheric conditions. The condition of this litter[5] is determined indirectly from measurements of air temperature and humidity or, more commonly, is determined directly by means of calibrated "wood sticks," the moisture content of which changes in harmony with that of natural fuels similarly exposed. The moisture content of heavy fuels, such as large branches, logs of all sizes, snags, and deep, buried layers of duff, changes slowly, and its measurement requires different techniques. In some regions it goes through a seasonal cycle, so that calendar date is a good index of cumulative drying. Elsewhere, elapsed time since rains of different amounts serves as an index. The seasonal cycle differs between north- and south-facing slopes and between steep and gentle slopes, according to the

[1] Received for publication December 7, 1942.

[2] "Forest fire danger" as used here, is a general term signifying the combination of variable elements that determines whether fires will start, and if so, the probable rate of spread and extent of damage.

[3] Italic numbers in parentheses refer to Literature Cited, p. 175

[4] Jemison, G. M., The measurement of forest fire danger in the eastern United States and its application in fire prevention and control. Appalachian Forest Exp. Sta. Tech. Note 50, 59 pp., illus. 1942. [Processed.]

[5] Litter is the uppermost layer of organic materials in the forest floor, the structure of which has not been materially altered by decomposition.

position of the sun, hence, the effectiveness of radiation. Another important element in fuel moisture conditions is stage of development of forest vegetation—the living fuel. This is ordinarily gaged by calendar date, ocular estimate, or actual measurement in the laboratory.

Determination of the best methods for measuring the moisture content of all types of fuels requires a knowledge of the interplay of controlling factors. For example, standards of how, where, and when to measure litter moisture and heavy fuel moisture cannot be established unless the controls of rates of drying and moisture equilibria are understood.[6] The weight that each fire-danger element should carry in the final rating, also, can be determined accurately only when the interactions of all controlling factors are known. The significance of season, elapsed time since rain, and similar indirect indices of fuel moisture depends on how the complex fuels of a given region react to the combined effect of the atmospheric factors. Furthermore, knowledge of the interaction of controls is needed in applying the ratings. In order to utilize efficiently the manpower available for fire suppression, a dispatcher needs to know how to adjust the rating available for his locality to allow for variations in temperature, humidity, and radiation brought about by variations in cover or topography in other parts of his district not served by a danger station. A fire boss on the fire line needs to be able to adapt danger ratings based on measurements taken elsewhere to fuel and weather conditions for areas in the path of the fire.

Although considerable effort has been made in the past to isolate the influence of each weather element, very little has been done to determine the effect of solar radiation on rates of drying of fuels and on the moisture equilibria of these fuels. The influence of shade on fuel and micro-climate has been discussed frequently. Stickel (*15*) obtained data confirming the importance of a timber canopy in maintaining high fuel moistures. He also found that in the mixed-hardwood-softwood forest region of the west-central Adirondacks, evaporation, hours since rainfall, duff temperature, air temperature, depression of the dew point, and relative humidity are most closely associated with litter moisture, in the order given. Mitchell (*14*) rated the general influence of individual weather elements on fuel moisture in the Lake States and showed how forest cover modifies atmospheric factors and hence fuel moisture. Jemison (*12*) found that absolute atmospheric moisture alone explained about as much of the variation in litter moisture content as did 15 weather factors combined. The work of these and other investigators brought out only indirect evidence, however, of the importance of solar radiation as a control of fuel moisture.

Gast and Stickel (*6*) were probably the first to investigate specifically the effect of sunlight on the rate of drying of forest fuels and consequently on fire danger. They compared fuel moistures in the open with those under the shade of bobbinet screens and found that the reduced radiation resulted in slower drying rates. From these investigations they concluded that degree of cloudiness could be used to gage fire danger and also that the amount of shade-producing cover on a cut-over area is an important criterion of the relative danger (dryness) on the area.

[6] Equilibrium moisture content may be defined as the asymptotic value which the actual moisture content approaches if the litter is subjected to a given temperature and humidity for an infinite length of time.

Hayes (*11*) measured air temperature, relative humidity, wind, litter moisture, maximum litter temperature, precipitation, and soil moisture on north and south slopes at each of three elevations in northern Idaho, and made a comparison of conditions as regards the first six of these elements on north slopes with those on south slopes. His results showed significant differences between the two aspects for all six elements except precipitation. He pointed out the importance of insolation as a control of fuel moisture, as indicated by measurements of maximum litter temperature. On south slopes, he found minimum litter moisture sometimes varied less than ± 1 percent from one clear day to the next, although maximum air temperature might range from 70° to 95° F., and minimum relative humidity from 30 to 15 percent. Hayes found that beds of pine duff on south slopes had a minimum moisture content, for a median day in August, about 2 percent lower than that of comparable beds on north slopes. His data indicate appreciable differences in fire behavior indices on north and south slopes.

The importance of solar radiation as controlling fuel moisture was mentioned by Byram (*3*). Radiation caused sticks exposed in calm air to dry rapidly. On wood sticks exposed to full sunlight, the drying action of wind was more than offset by its cooling action. Gisborne (*7*) found that sticks lying on litter were drier than those supported 10 inches above the litter surface, where circulation of air was greater.

An investigation of the influence of solar radiation on the moisture equilibria and rates of drying of forest fuels was begun by the Appalachian Forest Experiment Station in 1938, at the Bent Creek Experimental Forest, on the Pisgah National Forest, near Asheville, N. C. The investigation has included study of the effectiveness of radiation as a control of fuel moisture during different hours of the day and seasons of the year, on slopes of varied steepness and aspect. Theoretical relations between solar radiation and fuel moisture equilibria have been established and have been checked by field and laboratory experiments.

Under natural conditions, of course, fuel moisture is seldom in a state of equilibrium, but is usually increasing or decreasing. However, fuels with large exposed surfaces, such as hardwood leaf litter, approach the equilibrium moisture content after rain rather quickly. The rate of loss of moisture from forest litter in the southern Appalachian region on sunny days is so rapid that this layer of fuels may be considered as being in the equilibrium state most of the time.

The following technical discussion is intended to enable fire specialists to understand better the importance of radiation as a control of fuel moisture, and indicates work yet to be done on the problem. Suggestions are offered for use of the data, which may lead to refinements in some fire-control practices.

EXPERIMENTAL APPARATUS AND METHODS

In order to supply necessary constants in equations derived in this study, as well as to establish the effect of radiation on fuel moisture under a variety of topographic and atmospheric conditions, an "artificial sun" was constructed. This apparatus is actually a weather synthesizer, simulating variations of sunshine and wind, and making it possible to obtain quickly the effect of radiation as

modified by topography on fuel moisture equilibria. It renders unnecessary the impractical alternative of measuring directly in the field the response of fuel moisture to numerous combinations of weather elements on several kinds of slope throughout a year.

Two such artificial suns are shown in figure 1. The walls of the artificial sun enclose a rectangular volume divided by a horizontal glass plate into upper and lower compartments. The lower and shallower compartment, open at both ends and at the bottom, serves as a wind tunnel. At the top of the larger compartment, twelve 150-watt tungsten bulbs are placed on the perimeter of a circle to provide radiation. It has been shown mathematically that a circular source of light or radiation gives uniform distribution of energy on a surface parallel to the plane of the source and situated at a distance from that plane equal to the radius of the circle. As the radius in this case was

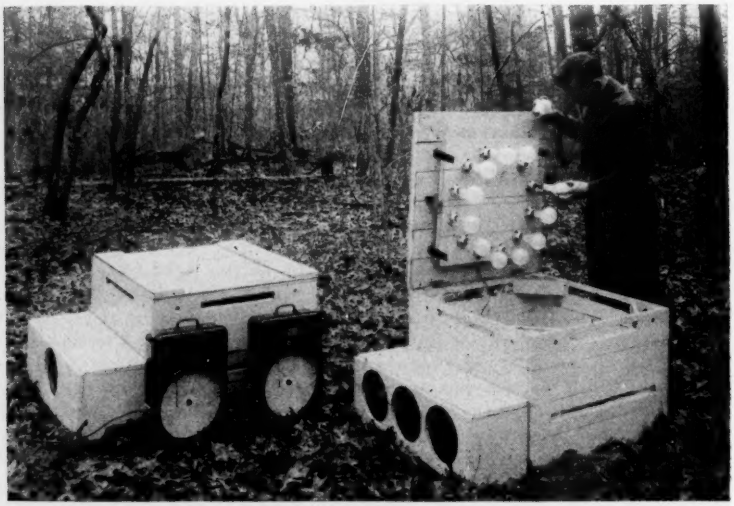

FIGURE 1.—Two artificial suns, or weather synthesizers.

9 inches, the bulbs were so placed that they were separated by a space of 9 inches from the leaf litter or other fuel tested. The whole interior of the apparatus was painted white, with the result that energy was uniformly distributed on the fuel even when only two or three bulbs were burning. The uniformity of radiation at the fuel surface was verified by careful checks with a photronic cell. The apparatus was placed directly over the natural litter in the forest or over fuel samples in the laboratory. Electric fans were used to draw air through the wind tunnel and over the fuel. Wind velocity was varied by adjusting the number of fans in operation or the openings in the box immediately behind them. Intensity of radiation was varied by turning on or off some of the bulbs; three or four bulbs, evenly spaced in the circle, were turned on or off at a time.

Usually two of the artificial-sun devices were operated simultaneously, so that results could be checked, or one of the three factors wind, radiation, and precipitation (simulated) could be varied while

all other factors were held constant. Wet- and dry-bulb temperatures were taken outside the apparatus, 6 to 8 inches above the ground, with a hand-aspirated psychrometer. Within the artificial sun, surface fuel temperature was measured by means of a recording thermometer, the ⅛-inch cylindrical bulb of which was placed on the litter and covered with a single thickness of oak leaves. Leaf samples were periodically collected, weighed, and oven-dried, and the moisture content computed on the basis of oven-dry weight. Tests varied in length from 2 hours to 2 days, according to the time required for the moisture content of the fuels to reach equilibrium.

Intensity of radiation was measured with the ice calorimeter (fig. 2), a device composed of two identical ice-containing units, each unit consisting of a thin-walled copper cup blackened inside and heavily insulated. Each insulated lid has a 2-inch hole at its center. One hole is uncovered, to admit radiation; an insulated shade excludes

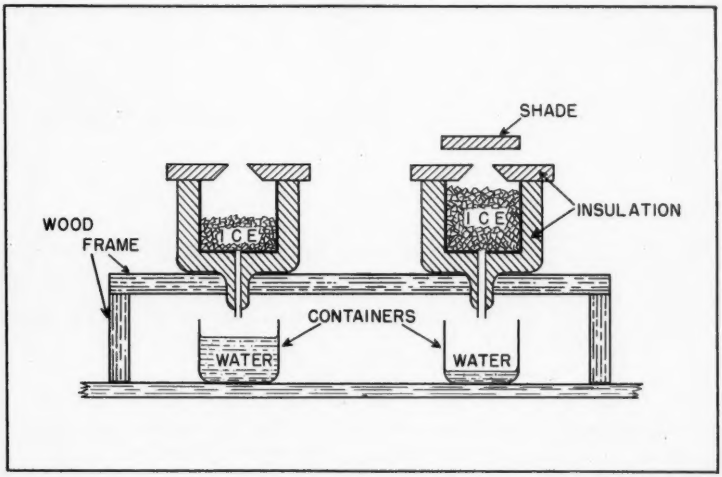

FIGURE 2.—Ice calorimeters used to measure intensity of radiation.

radiation from the other unit. Both units are exposed to the light source in the enclosed chamber of the artificial-sun apparatus. In use, each cup is two-thirds filled with ice. The difference in the number of grams of water draining from the two in a given time interval, multiplied by the heat of fusion of ice, gives the total radiant energy in calories admitted by the opening in the calorimeter lid during this interval. This energy, expressed in calories per square centimeter per minute, closely approximates the energy of solar radiation. Ten of the 150-watt bulbs gave 1.53 calories per square centimeter per minute, equivalent to very bright sunlight.

INTENSITY OF SOLAR RADIATION

The intensity of sunlight, varying with time of day, time of year, slope, aspect, latitude, and haziness of the atmosphere, can conveniently be expressed as a fraction of the theoretical maximum intensity or that received by a horizontal plane at the top of the atmosphere when the sun is at the zenith.

INTENSITY AS DETERMINED BY POSITION OF SUN, ASPECT, AND SLOPE

If atmospheric absorption is ignored, the intensity of solar radiation on a horizontal surface can be computed from the geometric position of the sun with respect to the surface. The sky may be regarded as a hemisphere, the lower boundary of which is the plane of the horizon.

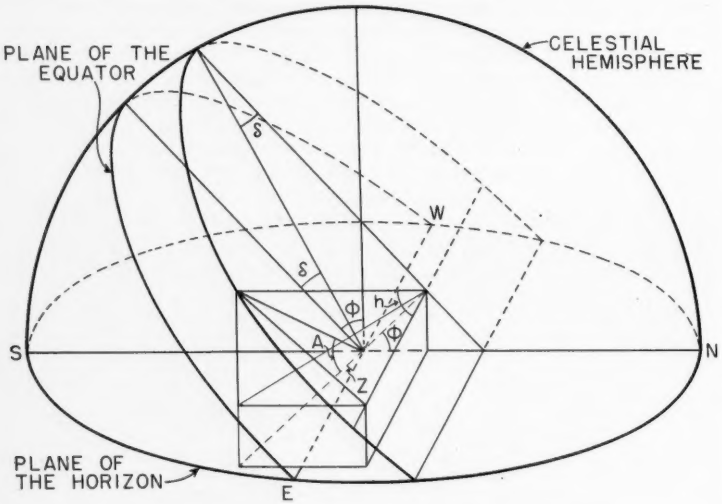

FIGURE 3.—Diagram of celestial hemisphere.

The daily paths of the sun are arcs on this hemisphere, as shown in figure 3. The angular altitude A of the sun is given by the equation

$$\sin A = \cos \delta \sin h \cos \phi + \sin \phi \sin \delta \qquad (1)$$

where δ is the solar declination, h the hour angle[7] (measured from 6 a. m.), and ϕ the latitude. The azimuth Z of the sun's position is given by the equation

$$\cos Z = \frac{\cos \delta \cos h}{\cos A} \qquad (2)$$

Figure 4 shows diagrammatically the conditions that exist when sunlight falls on a plane (mountain slope) tilted at some angle α from the horizontal and rotated clockwise through an angle β with respect to the east. The direction of the sun is along the line BC in the vertical plane CEB, and the lines BD and BE are the intersections of this plane with the tilted plane DHG and the horizontal plane EFG,

[7] In the standard equations given in a solar ephemeris or in most civil engineering handbooks or texts such as Breed and Hosmer (*1*), from which equations (1) and (2) can be derived, the hour angle is measured from noon and the azimuth angle is measured clockwise from north. However, in this study it was more convenient to measure the hour angle from 6 a. m. and the azimuth angle clockwise from east.

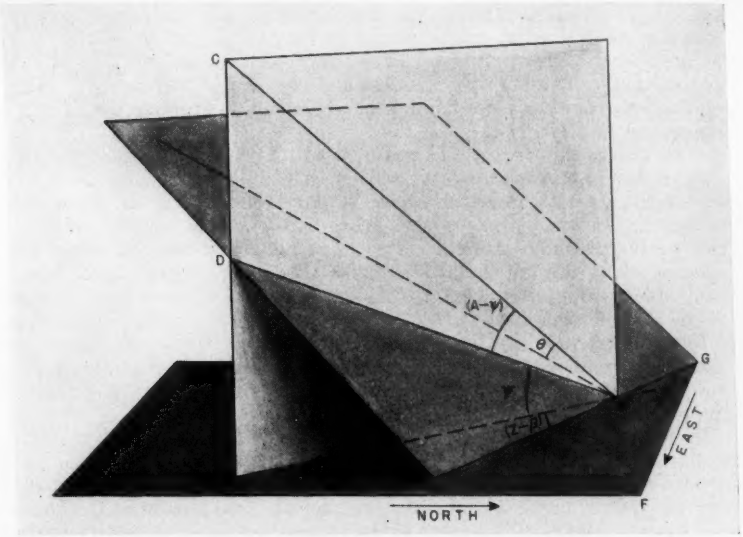

FIGURE 4.—Diagram from which the theoretical intensity of solar radiation on a tilted plane may be determined.

respectively. The angle *FGH* is the aspect angle β. For a mountain slope facing northeast, the aspect angle would be 45°; for one facing east, 90°; north, 0°; southwest, 225°. The intensity of radiation on the plane *DHG* is proportional to sin θ, which is given by the equation

$$\sin \theta = \sin (A-\psi)\frac{\cos \alpha}{\cos \psi} \tag{3}$$

the angle θ is the angle between the direction of the sun *BC* from a given point *B* in this plane and the projection of *BC* on the plane. Angle ψ is the angle between the projection of *BC* on the horizontal plane and the line *DB* formed by the intersection of the vertical plane and the tilted plane; tan ψ is given by the equation

$$\tan \psi = \sin (Z-\beta) \tan \alpha$$

which, when combined with equation (3), gives

$$\sin \theta = \sin A \cos \alpha - \cos A \sin \alpha (\sin Z \cos \beta - \cos Z \sin \beta) \tag{4}$$

EFFECTIVE RADIATION

The total amount of solar heat actually reaching the earth's surface is affected by atmospheric absorption of radiation. According to the law of absorption and Lambert's cosine law, the effective radiation received on any slope can be found from the equation

$$I = I_o \sin \theta \, p^{\frac{1}{\sin A}} \tag{5}$$

where *I* is the incident intensity of radiation on a tilted plane at the surface of the earth, I_0 is the intensity of radiation at normal incidence

on a horizontal surface at the top of the atmosphere, and p is the fraction of radiation transmitted at normal incidence through the atmosphere. The quantity I_0, the solar constant, equals 1.94 calories per square centimeter per minute according to Forsythe (*5*). However, it is often more convenient to express I_0 as unity so that I can be expressed as a fraction of I_0.

The absorption factor p is not constant from place to place or from day to day in a given locality, because it is affected by a large number of conditions such as water vapor, smoke, and dust in the air, and by altitude. In this study p was given an estimated value of 0.7, a reasonable average for a thin layer of rather dense haze, which is common at elevations of 2,000 feet in the southern Appalachian Mountains during the fall and spring fire seasons. In western forest regions of the United States the values of p may average somewhat higher than 0.7, although it is doubtful that they can ever be much above 0.8 except at great elevations. As defined and used in equation (5), p is independent of the vertical distribution of absorbing haze particles and the angular altitude of the sun.

The quantity I/I_0, which expresses the fraction of total possible radiation that actually reaches the earth's surface as determined from equation (5), has been presented in figure 5 as a function of time of day for typical combinations of slope, aspect, and season in the southern Appalachians. (The hour of maximum radiation intensity is that when the sun's rays approach the nearest to a 90° angle with the plane of the slope.) Curves showing fractions of maximum radiation received on 20-, 40-, and 100-percent south, north, and east slopes are plotted for June 21 and December 21, dates when the sun reaches its greatest and least angular altitudes. For the calculations represented in determining sin A, a latitude of 35°30′ was assumed. Solar declinations were obtained from a solar ephemeris, northern and southern declinations having the customary positive and negative signs, respectively.

The differences in radiation on north and south slopes brought out by figure 5 are particularly significant because direct sunlight is the greatest factor in drying exposed forest fuels. In deciduous forests or on clear-cut conifer forest areas in the eastern mountain regions, fuels are unshaded, or practically unshaded, during several months of the year. The hardwood stands are leafless from November into May, or even longer at some elevations and latitudes, and this period includes the major part of the annual fire season. On clear-cut or severely burned forest areas in the West, fuels are completely exposed to the sun throughout the fire season. Obviously, if ground fuels are partially shaded by a forest canopy, radiation intensity as represented in figure 5 is modified.

Among the southern exposures, in summer the 20-percent slope receives the greatest radiation, because this slope forms an angle of almost 90° with the sun's rays at noon. The 100-percent slope is too steep to receive maximum radiation at this hour. In winter, however, when the sun is low, the 100-percent slope receives more radiation than either the 20- or the 40-percent slope. Curves for other seasons of the year would fall between those shown for June 21 and December 21.

The picture for north-facing slopes is somewhat different. At the latitude of the southern Appalachians, where the sun approaches the

zenith on June 21, 20-percent north slopes receive almost as much radiation in the summer as 20-percent south slopes. On 100-percent north slopes, however, the radiation at noon on that date is 0.38 of the maximum, as compared with 0.58 on south slopes of the same steepness. On December 21, 100-percent north slopes are in complete topographic shade, whereas 100-percent south slopes receive about 0.48 of maximum radiation at noon.

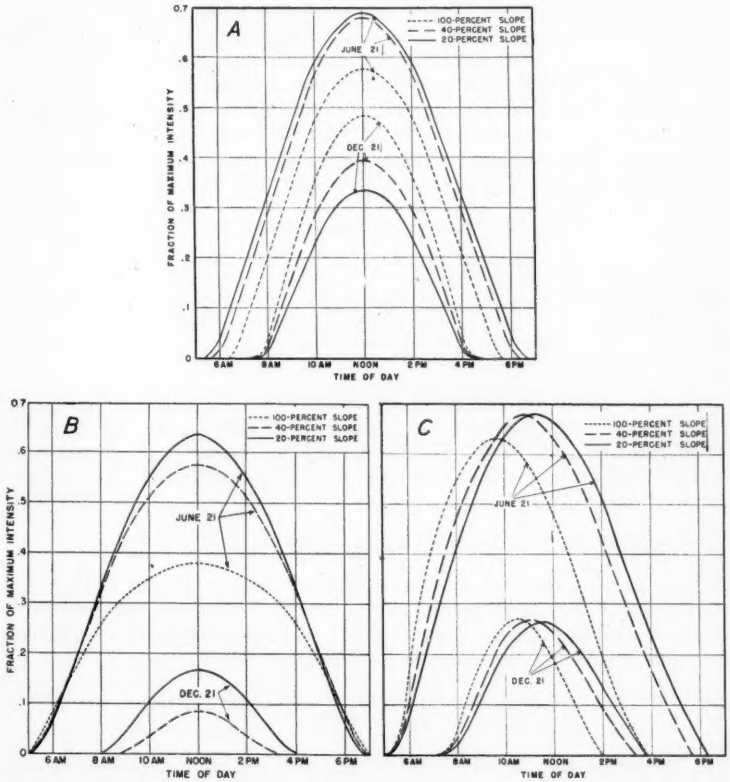

FIGURE 5.—Intensity of radiation received at different times of day on (*A*) south, (*B*) north, and (*C*) east slopes in the southern Appalachians, on June 21 and on December 21.

On east slopes, radiation intensity reaches its maximum before noon. For west slopes the curves would be mirror images of those for east slopes, the maxima occurring in the afternoon.

An example of the calculation of I, effective radiation received on a given surface, is presented as a guide to technicians who wish to adapt equations (1) to (5) to other regions of the United States.

Problem: To find radiation I, for a 20-percent east slope at 10 a.m. on June 21 at a north latitude of 35°30′.

Given: Hour angle $h=60°$ (measured from 6 a.m.).
Latitude $\phi=35°30'$ (assumed).
Aspect angle $\beta=90°$ (measured from north).
Angle of slope $\alpha=11°19'$ (for an assumed 20-percent slope).
Solar declination $\delta=23°30'$ (from solar ephemeris tables).
Solar constant $I_o=1$.
Absorption factor $p=0.7$ (assumed).

The following computations are sufficient for determining I. The sines and cosines of A and Z are found from equations (1) and (2) respectively. Sin θ is computed by means of equation 4 from the sines and cosines of A, Z, α, and β. The radiation I is then computed from equation (5). The details of these steps are as follows:

$$\text{Sin } A=\cos 23°30' \sin 60° \cos 35°30'+\sin 35°30' \sin 23°30'$$
$$=.878, \text{ and } \cos A=.478.$$

$$\text{Cos } Z=\frac{\cos 23°30' \cos 60°}{.478}$$
$$=.958, \text{ and } \sin Z=.287.$$

$$\text{Sin } \theta=.878 \cos 11°19'-.478 \sin 11°19' (.287 \cos 90°-.958 \sin 90°)$$
$$=.951.$$

$$I=.951\ (.7)^{\frac{1}{.878}}$$
$$=0.63 \text{ of maximum possible radiation.}$$

The value 0.63 thus derived checks with that plotted in figure 5, for the conditions assumed. To obtain the value I in calories per square centimeter per minute, 0.63 would be multiplied by the solar constant given by Forsythe, 1.94.

SOLAR RADIATION AND EQUILIBRIUM FUEL MOISTURE

To determine the quantitative relation between solar radiation and fuel moisture it was necessary to analyze the relations between temperatures and humidities of the fuel bed and the independent variables, air temperature, air humidity, wind, and insolation.

RELATIONS OF RADIATION AND WIND TO TEMPERATURE DIFFERENCE OF FUEL AND AIR

If $\frac{dQ_l}{dt}$ is the rate at which a fuel sample in sunlight loses heat and $\frac{dQ_g}{dt}$ is the rate at which it gains heat, then the temperature of the fuel sample remains stationary only if

$$\frac{dQ_l}{dt}=\frac{dQ_g}{dt} \tag{6}$$

According to Newton's law of cooling, the rate of loss of heat from an object is directly proportional to the temperature difference existing between the object and its surroundings, and includes rates of loss due to free convection, conduction, and radiation. If the temperature difference is not very great, the radiation loss is small compared with the loss due to convection and conduction. This law can be generalized

to give the rate of loss due to forced convection when the object is ventilated by an appreciable wind. If it is assumed that rate of loss of heat from forest fuels is directly proportional to wind velocity, it is possible to write the equation

$$\frac{dQ_l}{dt}=(aV+b)(T_f-T_a) \tag{7}$$

where V is wind velocity, T_f is fuel temperature, T_a is air temperature, and a and b are constants. The values of the constants a and b depend to a considerable extent on the nature of the fuel bed and the manner in which T_f is measured. In this study, for example, the value for T_f, the temperature of the air in the spaces under the topmost individual leaves, is considerably less than would be shown by a thermocouple with the junction cemented to the upper surface of a leaf. In addition, considerable heat is lost by conduction through the fuel bed into the ground. Radiation losses from forest fuels are small.

If I is the intensity of radiation in calories per square centimeter per minute as measured in the artificial-sun apparatus, and if this is the only source of heat, then from equations (6) and (7)

$$\frac{dQ_l}{dt}=\frac{dQ_s}{dt}=I=(aV+b)(T_f-T_a) \tag{8}$$

from which

$$T_f-T_a=\frac{I}{aV+b} \tag{9}$$

The relation between T_f-T_a and I for different wind velocities as established experimentally with the artificial-sun apparatus, is shown in figure 6 in which measured values of T_f-T_a are plotted against

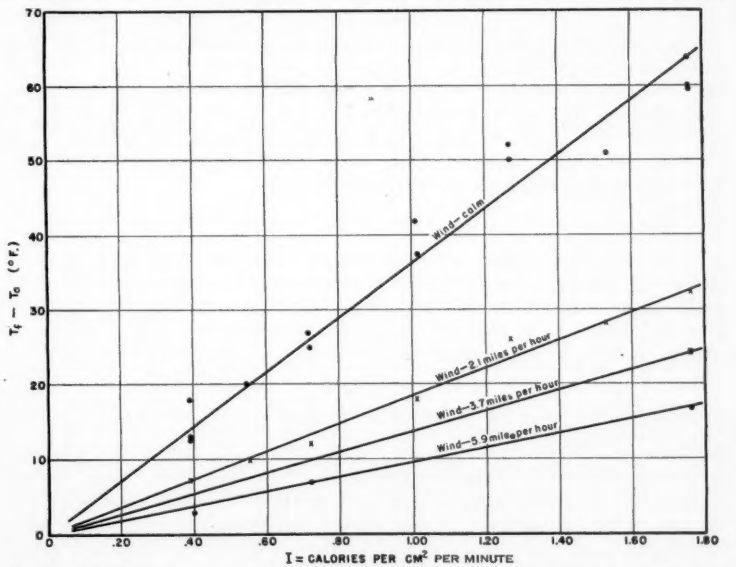

FIGURE 6.—Relation of radiation intensity I and wind velocity V to difference between fuel temperature and air temperature T_f-T_a, as established experimentally with the artificial-sun apparatus.

TABLE 1.—*Experimental data used in determining relation of T_f-T_a to radiation intensity and wind velocity*

Radiation intensity, I (calories per cm² per minute)	Wind velocity, V	Air temperature, T_a	Surface fuel temperature, T_f	Temperature difference, T_f-T_a	Radiation intensity, I (calories per cm² per minute)	Wind velocity, V	Air temperature, T_a	Surface fuel temperature, T_f	Temperature difference, T_f-T_a
	M. p. h.	°*F.*	°*F.*	°*F.*		*M. p. h.*	°*F.*	°*F.*	°*F.*
0.39	0	79	92	13	1.01	2.1	84	102	18
.39	0	78	91	13	1.01	3.7	77	94	17
.39	0	79	97	18	1.27	0	74	124	50
.39	2.1	79	86	7	1.27	0	70	122	52
.39	5.9	79	82	3	1.27	2.1	74	100	26
.56	0	90	110	20	1.27	5.9	70	83	13
.56	2.1	90	100	10	1.53	0	75	126	51
.72	0	80	107	27	1.53	2.1	75	103	28
.72	0	84	109	25	1.76	0	77	137	60
.72	2.1	84	96	12	1.76	0	80	140	60
.72	5.9	78	85	7	1.76	0	83	146	63
1.01	0	77	119	42	1.76	2.1	76	108	32
1.01	0	83	120	37	1.76	5.9	83	100	17

measured values of I. The ranges in air temperature, fuel temperature, wind, and radiation under which observations were made are as follows: Air temperature, 74° to 90° F.; fuel temperature, 83° to 146° F.; wind, 0 to 5.9 miles per hour; radiation intensity, 0.39 to 1.76 calories per square centimeter per minute. Data forming the basis for figure 6 are given in table 1. Computing the constants a and b by the method of least squares gives for equation (9), when T_f-T_a is in degrees Fahrenheit,

$$T_f-T_a=\frac{I}{0.015\ V+0.026} \tag{10}$$

which adequately fits the experimental data. When a and b are determined directly from the data, it is not necessary to know the total emissivity or absorption factor of the fuel bed. It should be emphasized that, in fuel types in which loss of heat to the soil underlying the litter and loss to the air proceed at faster or slower rates than in the beds of hardwood leaf litter used in this investigation, other values for the constants a and b would be obtained.

RELATIONS OF RADIATION, HUMIDITY, AND WIND TO FUEL MOISTURE

The relation of radiation and relative humidity to fuel moisture can most easily be determined by means of the vapor pressure function. If the range of temperature is not too great, the saturated vapor pressure P_s in a given space at a temperature T is related to T approximately by the empirical equation

$$P_s=Ke^{cT} \tag{11}$$

where P_s is in millimeters of mercury, T is in degrees Fahrenheit, e is the base of natural logarithms, and K and c are constants. Table 2 shows the saturated vapor pressure of water for temperatures from 32° to 122° F. and corresponding values of Ke^{cT}, when K and c have values of 1.77 and 0.033, respectfully. That these assumed values provide a close approximation of P_s is seen by comparing the second and third columns in the table; the values agree closely except at high temperatures. The values of K and c in equation (11) could be altered slightly throughout the temperature range of, say, 60°

to 150°, which would be more suitable for use in summer, when fuel and air temperatures are high. This adjustment is unnecessary, however, because through a temperature range of 100° equilibrium fuel moisture values are changed only to the extent of about one-third of 1 percent by errors in the constant c. The constant K does not enter into determinations of fuel moisture equilibria.

TABLE 2.—*Saturated vapor pressure of water for temperatures 32° to 122° F. and corresponding values of Ke^{cT} when $K=1.77$ and $c=0.033$*

Temperature (°F.)	Saturated vapor pressure of water	Ke^{cT}	Temperature (°F.)	Saturated vapor pressure of water	Ke^{cT}
	Mm. of Hg	*Mm. of Hg*		*Mm. of Hg*	*Mm. of Hg*
32	4.58	5.09	86	31.82	30.22
41	6.54	6.85	95	42.18	40.69
50	9.21	9.22	104	55.32	54.76
59	12.78	12.40	113	71.88	73.70
68	17.54	16.69	122	92.51	99.18
77	23.76	22.47			

The vapor pressure P existing when the space is not saturated is related to P_s by the equation

$$P=HP_s \tag{12}$$

where H is the relative humidity. Hence, if P_a is the pressure of the water vapor in a given space at air temperature T_a and relative humidity H_a,

$$P_a=H_aKe^{0.033T_a} \tag{13}$$

and if P_f, T_f, and H_f refer to the same properties in a space immediately adjacent to the fuel particles,

$$P_f=H_fKe^{0.033T_f} \tag{14}$$

But when fuel moisture is in equilibrium, P_a and P_f are equal, hence (13) and (14) can be combined, which gives

$$\frac{H_f}{H_a}=e^{-0.033\ (T_f-T_a)} \tag{15}$$

Substituting (10) in (15) gives

$$\frac{H_f}{H_a}=e^{-I/(0.39V+0.85)} \tag{16}$$

Solutions for $\frac{H_f}{H_a}$ can be found from the nomographic chart figure 7. If any given values of V and I are connected with a straight edge, solutions for the ratio $\frac{H_f}{H_a}$ are given by the intersection of the straight edge with the line representing $\frac{H_f}{H_a}$. The value of H_f can be found from the ratio if H_a is known.

544208—43——3

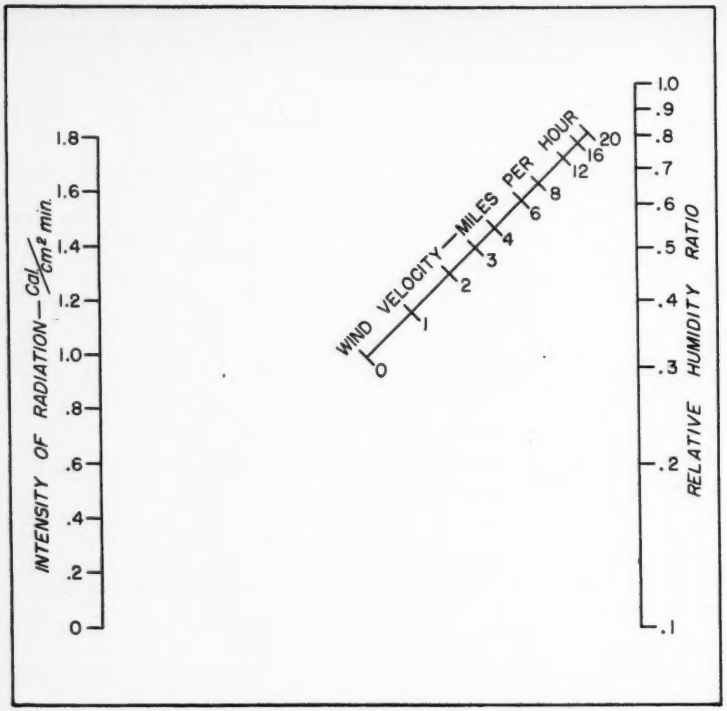

FIGURE 7.—Nomographic chart for solving the equation

$$\frac{H_f}{H_a}=e^{-1/(0.39V+0.85)}$$

The equilibrium moisture content of forest fuels (and cellulose materials in general) is determined chiefly by relative humidity, although temperature has considerable influence. From figure 8, which applies to any finely divided fuel,[8] equilibrium fuel moisture content can be found if fuel temperature T_f and fuel humidity H_f are known. With no sunlight, or if the fuel is completely shaded, fuel temperature and humidity are approximately the same as air temperature and humidity. Under either of those conditions, figure 8 may be used to find equilibrium fuel moisture by considering that $T_f=T_a$ and that $H_f=H_a$.

It is possible to determine fuel moisture equilibria for any given combination of air temperature, relative humidity, wind, and radiation by computing the effective temperature T_f and effective humidity H_f and applying these to figure 8. For example, what is the fuel moisture equilibrium when air temperature is 80°F., atmospheric relative humidity is 30 percent, wind velocity is 0, and radiation intensity is

[8] Except for high moisture contents, figure 8 checks closely with a fuel moisture equilibrium chart for Sitka spruce wood given by L. F. Hawley (*10, p. 8*), and with a series of similar relations for several kinds of light fuel reported in the following: DUNLAP, M. E. THE RELATION OF HUMIDITY TO THE MOISTURE CONTENT OF FOREST FIRE FUELS. U. S. Forest Serv., Forest Prod. Lab. 9 pp., illus. 1924. (Unpublished).

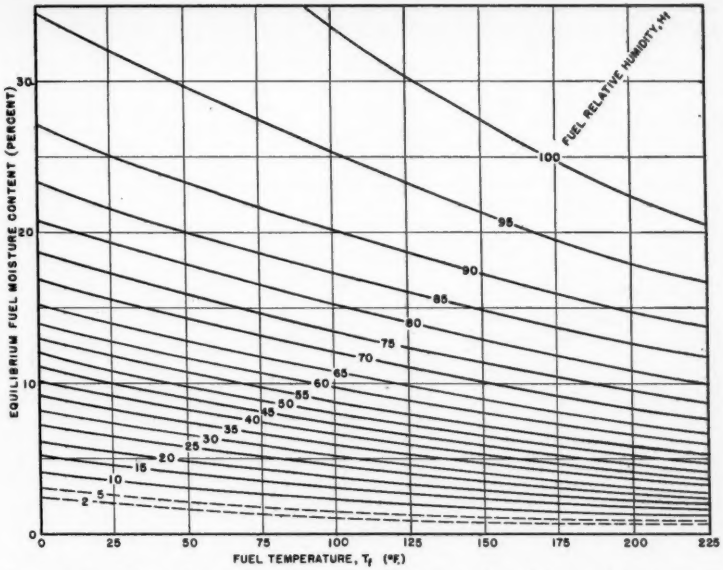

FIGURE 8.—Chart for determining equilibrium fuel moisture content on the basis of fuel humidity and fuel temperature. (Adapted from chart based on results of experimental work by the U. S. Forest Products Laboratory and published in the following: GRAY, L. G. PRELIMINARY REPORT ON FIRE HAZARD RATING STUDY. U. S. Weather Bur. San Francisco. 1933. [Processed.] The broken lines have been added by extrapolation.)

0.80 calories per square centimeter per minute on a slope fully exposed to the sun? From figure 6 the difference between litter and air temperature ($T_f - T_a$) is found to be 29°, which means that effective or fuel temperature is 109°. The relative-humidity ratio $\frac{H_f}{H_a}$ is found from figure 7 to be approximately 0.4. Effective humidity (at fuel surface) is then easily found; since

$$\frac{H_f}{H_a}=0.4 \text{ and } H_a=30$$

$$H_f=12 \text{ percent}$$

When 109° and 12 percent are used in figure 8 as the values for T_f and H_f, respectively, equilibrium fuel moisture is seen to be about 2.5 percent.

Under the conditions assumed above—air temperature of 80° F. and humidity of 30 percent—but with radiation intensity of 0, equilibrium fuel moisture as determined from figure 8 would be 6 percent. Thus, under these air conditions, where fuel in the sunlight would have an equilibrium moisture content of 2.5 percent, fuel in shade would have one of 6 percent.

Close agreement between equilibrium fuel moistures experimentally determined and those computed from figures 7 and 8 is indicated by the data presented in table 3. The experimental values are from 0

TABLE 3.—*Comparison of experimentally and theoretically determined fuel moisture equilibria for different combinations of radiation, wind, temperature, and humidity*

THIN BASWOOD SLATS

Radiation intensity, I (calories per cm.^{2} per minute	Wind velocity, V	Surface fuel temperature, T_f	Air humidity, H_a	Humidity ratio, H/H^a	Fuel humidity, H_f	Equilibrium fuel moisture	
						Theoretical [1]	Experimental [2]
	M.p.h.	*°F.*	*Percent*		*Percent*	*Percent*	*Percent*
0.39	0	97	78	0.62	48	7.7	7.7
.39	2.1	86	78	.80	62	11.0	11.1
.56	0	110	54	.52	28	4.3	5.3
.56	2.1	100	54	.71	38	6.2	6.6
.72	0	109	30	.42	13	2.5	3.6
.72	2.1	96	30	.64	19	3.6	4.7
1.01	0	120	50	.30	15	2.6	3.8
1.01	2.1	102	50	.55	28	4.7	5.4
1.27	0	124	60	.22	13	2.5	3.6
1.27	2.1	100	60	.48	29	5.2	5.3
1.53	0	126	58	.17	10	2.0	2.9
1.53	2.1	103	58	.40	23	4.2	5.3
1.76	0	137	56	.13	7	1.8	3.6
1.76	2.1	108	56	.34	19	3.5	4.3
1.76	0	135	60	.13	8	1.9	3.0
1.76	3.7	102	60	.58	35	5.9	5.9
1.76	0	146	54	.13	7	1.5	2.4
1.76	5.9	100	54	.57	31	5.2	6.4

HARDWOOD LEAF LITTER

1.76	0	160	47	0.13	6	1.8	2.8
1.76	5.7	98	47	.55	26	4.6	5.6
1.76	0	125	53	.13	7	2.0	2.7
1.76	6.5	91	53	.58	31	6.0	7.0

[1] Computed from figures 7 and 8.
[2] Determined by use of the artificial-sun apparatus.

to 1.8 percent higher than those computed from the graphs; the average departure is 0.8 percent. Undoubtedly, this difference was due partly to a slight lag in rate of drying but mostly to hysteresis.

EFFECT OF WIND ON MOISTURE EQUILIBRIA OF IRRADIATED FUELS

From equation (16) one would be inclined to deduce that fuels exposed to both radiation and wind have higher equilibrium moisture contents than fuels exposed to radiation in still air. Although contrary to the usual ideas of drying phenomena, this deduction is conclusively borne out by the fuel moisture curves in figures 9, 10, and 11, and by the data presented in table 3. Figure 9, based on data for thin basswood slats immersed in water and then exposed in artificial-sun apparatus, shows that the slats had higher equilibrium moisture contents in wind than in calm air. Figure 10 indicates a similar contrast between slats in wind and in calm air that were started at oven dryness. Figure 11 shows the rate of drying of hardwood leaf litter having an initial moisture content of about 20 percent, a value within the inflammable range. This fuel responds in a manner identical to that of the wood slats represented in figures 9 and 10.

The higher moisture equilibria of irradiated surface fuels subjected to wind are due to the higher humidities associated with lower fuel

temperatures. For irradiated fuels the cooling action of wind more than offsets its drying action. Figure 10 demonstrates that a cool fuel can absorb and hold more moisture than a hot one. (This is a partial explanation for the fact that higher moistures exist on cut-over areas bearing residual stands than on comparable clear-cut areas.)

The general conclusion may be drawn that, in regions where forest

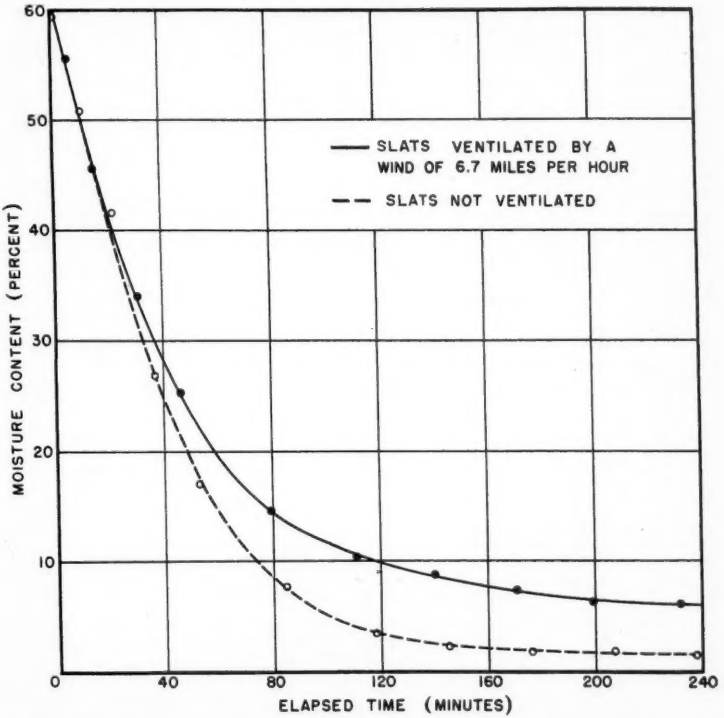

FIGURE 9.—Drying curves for irradiated wood slats exposed in calm air and for others exposed to a wind of 6.7 miles per hour. Slats were initially immersed in water. Relative humidity during test, 55 percent; air temperature, 80° F.; radiation, 1.76 calories per square centimeter per minute.

fuels are normally exposed to sunlight, higher fuel moisture equilibria are associated with clear windy weather than with clear calm weather. The difference may be as great as 6 percent, depending chiefly on levels of the atmospheric factors temperature, humidity, and wind. It is greatest for the range of fuel moisture below about 15 percent. This influence of wind operates only to a slight extent on steep north slopes, where insolation is low.

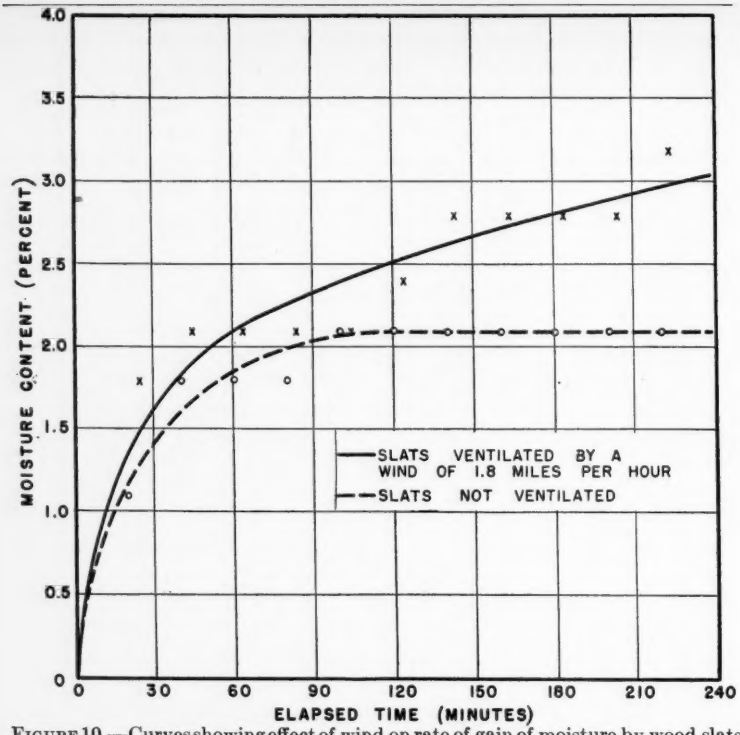

FIGURE 10.—Curves showing effect of wind on rate of gain of moisture by wood slats initially oven-dry and exposed to a radiation of 1.76 calories per square centimeter per minute. Relative humidity during test, 62 percent; air temperature, 82° F

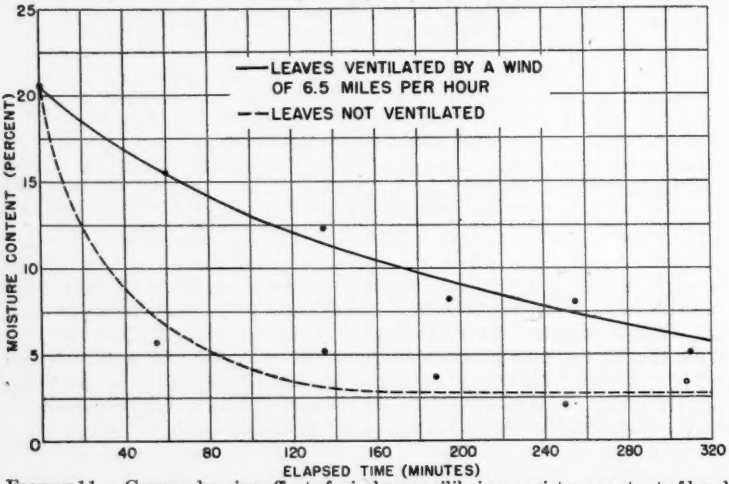

FIGURE 11.—Curves showing effect of wind on equilibrium moisture content of hardwood leaf litter exposed to a radiation of 1.76 calories per square centimeter per minute. Relative humidity during test, 51 percent; air temperature, 84° F.

SOLAR RADIATION AND RATE OF DRYING OF FOREST FUELS

As has been stated, the moisture content of the surface forest litter in the southern Appalachian region may be considered as being in the equilibrium state most of the time. The moisture content of lower layers of forest fuels, on the contrary, is not often in equilibrium with the humidity of the air immediately above the fuel bed; and it has almost as great an influence as that of the surface fuels in determining the inflammability of the total fuel layer. The rate at which subsurface fuels dry out after a rain is therefore particularly important. Only after determining the principles that govern this rate of loss of moisture can fire-research specialists supply fire dispatchers with guides that will enable them to judge when fuel is approaching an inflammable state. A complete solution of the rate-of-drying problem would find more immediate application than one of any other phase of fuel moisture studies.

Complete solution of the rate-of-drying problem is outside the scope of the present investigation, but this problem deserves discussion in connection with a general analysis of the factors upon which fuel moisture content depends. For the benefit of other investigators, some of the theoretical concepts of rate of drying of forest fuels will be outlined.

If q is the moisture content of a thin layer within a thick (about 2-inch) bed of fuel, the rate of loss of moisture from this layer should be given with reasonable accuracy by a differential equation of the form

$$\frac{dq}{dt}=-f_1(q)(P_f-H_aP_s)f_2(V)f_3(D) \qquad (17)$$

where P_f is the pressure of water vapor within the fuel layer, P_s the pressure of saturated water vapor at air temperature, H_a the relative humidity of the air at the surface of the fuel bed, $f_1(q)$ some undetermined function of fuel moisture, $f_2(V)$ some function of wind velocity V, and $f_3(D)$ some function of the thickness D of the fuel above the selected thin layer.

The evaporating force is proportional to the term $(P_f-H_aP_s)$, but the rate of evaporation depends also on the vapor pressure gradient existing between the fuel layer and the space immediately above the surface of the fuel bed. The vapor pressure gradient is determined in part by the thickness and porosity of the fuel above the layer under consideration, and in part by wind velocity. The rate of evaporation depends in some complex way on the water supply or on $f_1(q)$. The vapor pressure P_f in the fuel layer is a function of the temperature of the fuel layer, which in turn is determined by air temperature, wind velocity, intensity of radiation, and rate of evaporation $\frac{dq}{dt}$. If a temperature gradient exists in the fuel bed, P_f depends also on D. If the moisture content q is below the fibre saturation point (about 30 percent) P_f is a function of q, since the water molecules in that case become partially bonded to the molecules of wood substance and this causes a decrease in P_f. For this reason equation (17) cannot easily be integrated if q is less than 30 percent. For values of q above the fibre saturation point, equation 17 can be integrated as follows, pro-

vided that the rate of loss of heat due to evaporation cooling is small compared with the intensity of radiation:

$$\int_{q_o}^{q} \frac{dq}{f_1(q)} = -(P_f - H_a P_s) f_2(V) f_3(D) \int_{o}^{t} dt$$

or

$$F(q_o) - F(q) = (P_f - H_a P_s) f_2(V) f_3(D) t \tag{18}$$

where $F(q)$ is the integral of $f_1(q)$.

To find the time required for two similar layers of fuel to lose equal amounts of water under different intensities of radiation and wind velocities, it is possible to write

$$F(q_0) - F(q) = (P_f - H_a P_s) f_2(V) f_3(D) t = (P'_f - H_a P_s) f_2(V') f_3(D) t'$$

or

$$(P_f - H_a P_s) f_2(V) t = (P'_f - H_a P_s) f_2(V') t' \tag{19}$$

where P'_f, V', and t' are fuel vapor pressure, wind velocity, and time, respectively, for the second fuel layer. P_f and P'_f must be the saturated vapor pressures corresponding to the fuel temperatures, and should be regarded as the vapor pressures existing on the surface of individual wet leaves in the fuel layers. After substitution of the exponential relation (equation 11) for vapor pressures and simplification, equation (19) becomes

$$[e^{c(T_f - T_a)} - H_a] f_2(V) t = [e^{c(T'_f - T_a)} - H_a] f_2(V') t'$$

Substituting $\frac{I}{aV+b}$ for $T_f - T_a$ (equation 9) gives

$$\left[e^{\frac{cI}{aV+b}} - H_a\right] f_2(V) t = \left[e^{\frac{cI'}{aV+b}} - H_a\right] f_2(V') t' \tag{20}$$

When an assumed wind velocity value of 2.5 miles per hour was inserted in equation (19) along with the values of a, b, and c previously given, the equation was simplified to

$$(e^{0.54I} - H_a) t = (e^{0.54I'} - H_a) t' \tag{21}$$

Values computed from this equation for relative time required for thin layers of fuel near the surface of fuel beds on north and south slopes to lose equal amounts of moisture after a rain are presented in table 4.[9]

TABLE 4.—*Relative drying time* [1] *of fuel near surface of fuel bed on north and south slopes in May and November*

Slope (percent)	May 6		November 6	
	North	South	North	South
20	2.5	2	7	4
40	2.5	2	9	3.5
60	3	2	15	3.5

[1] Calculated by use of equation (21). Wind velocity of 2.5 m. p. h. and 40 percent relative humidity are assumed. Values may be regarded as either days or hours.

[9] According to the current results of a study to determine the effect of terrestrial radiation on fuel moisture, on most forest areas the ratios of time required for drying on north slopes to that required on south slopes may be considerably greater than indicated in table 4. Under some conditions, north slopes may actually gain moisture on calm, cloudless days and nights while adjacent south slopes continue to lose moisture. Equation (17) is sufficiently general to include in its solution the effects of terrestrial radiation on fuel moisture.

The tabular value of t, relative drying time, for a given slope and season of year is the reciprocal of the area between two curves plotted on the same graph, one representing hourly values of the quantity $e^{0.541}$, the other representing values of relative humidity H_a drawn as a smooth curve from 100 percent at sunrise to 40 percent at noon to 70 percent at sunset. It was assumed that no significant drying occurred during the night. The area between the two curves represents the integrated value of $e^{0.541}-H_a$ for the daylight hours.

Experimental data obtained with the artificial-sun apparatus show

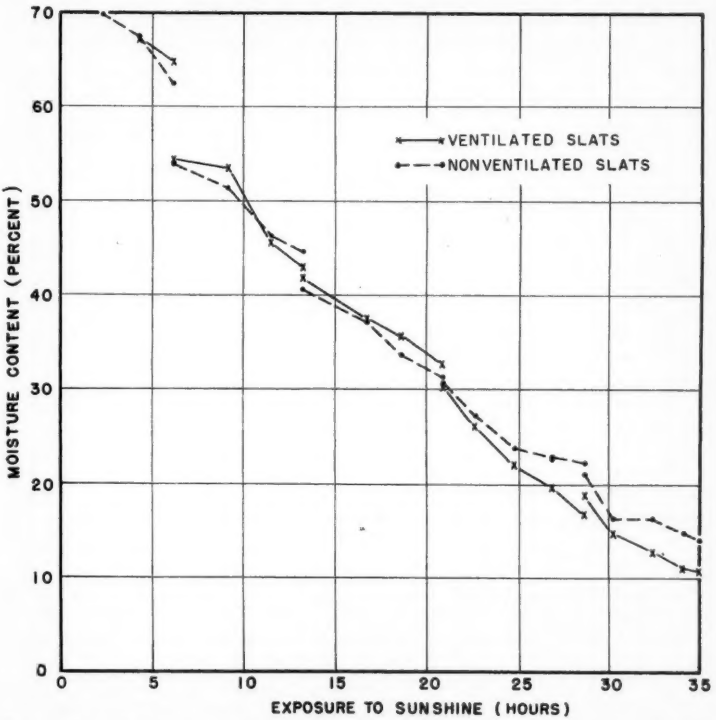

FIGURE 12.—Drying curves for lower layers of fuel exposed to radiation, as measured by thin slats buried in the lower layers of litter. (Breaks in curves indicate effect of turning off fans and lights in artificial-sun apparatus at night.)

that, in bright sunlight, winds of low velocities (1 to 3 miles per hour at the fuel surface) have no appreciable net effect on rate of drying of subsurface fuel. This is illustrated by drying curves for the lower fuel presented in figure 12. The same thing is true of basswood slats of high moisture content, as is shown by the portion of figure 9 representing moistures above the fibre saturation point. In this figure it will be noted that when their moisture content was above 30 percent, the slats dried at almost the same rate in calm air as in a wind of 6.7 miles per hour. A logical explanation is that although wind has a pronounced tendency to hasten drying this is offset, when wind velocity is low and radiation intensity is high, by its tendency to cancel the

influence of radiation on temperature, just as is the wind's tendency to lower the equilibrium moisture content of surface fuels. Figure 13, which shows the effect of wind on the rate of drying of basswood slats in the absence of radiation, indicates that this explanation is correct, because the fuel in wind dried faster than that in calm air.

Probably several other factors influence the form of the basic equation (18), and the values presented in table 4 may be only rough approximations. For example, the moisture gradient within a drying fuel bed is affected by the loss of moisture from all fuel layers, not just

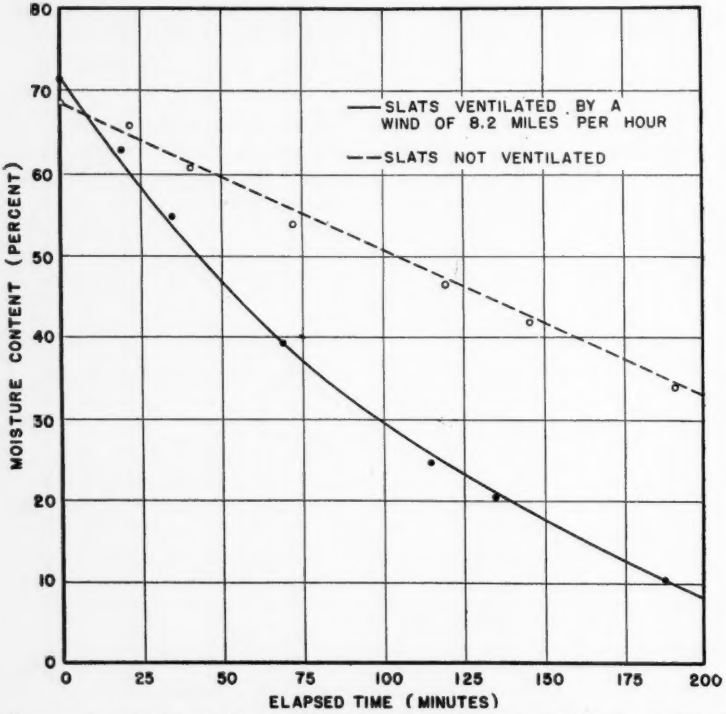

FIGURE 13.—Rates of drying of ventilated and nonventilated wood slats in absence of radiation.

one layer. However, equations (19) to (21) probably would not be changed appreciably by variation in the moisture gradient. A vertical temperature gradient also exists within a fuel bed, and $T_f - T_a$ is smaller for lower fuel layers than for layers near the surface. For thin basswood slats exposed so that the air can circulate freely about them, the rate of heat loss due to evaporation cooling is not small compared with the intensity of radiation received; it may occasionally be almost half as great as the radiation intensity. However, evaporation cooling is probably much less in fuel beds.

The development of rate-of-drying equations for moisture contents below the fibre saturation point is a phase of the problem that has

received relatively little attention from technical foresters, but is one of extreme importance.

Work on the entire rate-of-drying problem is continuing at the Appalachian Forest Experiment Station.

SIGNIFICANCE AND APPLICATION OF FINDINGS

As was mentioned in the introduction, fire-danger ratings are used as guides in the employment and disposition of fire-control personnel. When the weather becomes dry and windy, more lookout men and suppression crews are required—especially in the drier and windier parts of a forest. Danger ratings help fire-control administrators to estimate how many men they need and to distribute their forces advantageously. In order to increase the refinement with which forest fire-danger ratings are made and applied, one necessity is to gain a better understanding both of the influence of topography and of "season of the year" on fire danger. In the United States the significance of seasonal changes in radiation intensity is particularly great in northern latitudes; in hardwood forest types that are leafless during late spring, when radiation is intense; on areas of rugged topography; and on western burned-over areas where dead forest fuels are exposed to sunlight during the summer months. This paper provides technicians in all regions with a general technique and equations for computing moisture equilibria of surface fuels for any combination of date, hour, slope, aspect, air temperature, air humidity, and wind, and with information on some of the basic relations governing rate of drying. This should lead to a better understanding regarding these factors on the part of workers engaged in perfecting fire-danger rating systems. Eventually, by acquiring and using a knowledge of radiation effects, it should be possible to modify the several measurements made at a skeleton network of fire-danger stations to fit all topography adjacent to the stations, thus greatly reducing the labor and cost of danger measurements.

Rates of drying of forest fuels calculated in this study can be used as a partial correction for ratings of fire danger at key stations, to make them apply to areas where conditions cannot be measured. Table 4, compiled in connection with the theoretical development of rate-of-drying relations, brings out differences in rate of drying for several aspect-slope-season combinations. After a rain in early May, it indicates, the fuel on a 60-percent south slope in the southern Appalachians loses as much moisture in 2 days as that on a corresponding 60-percent north slope loses in 3 days. Likewise in November the fuel on the south slope dries from a saturated condition down to an inflammable one in 3½ days, but the fuel on the north slope does not reach this point until after 15 days of the same type of weather.

Rate-of-drying data will become especially valuable to fire-control administrators when more is learned about variations in effect of wind corresponding to topographic variations and about variations in temperature and humidity corresponding to variations in elevations. Hayes (*11*) has worked on the latter problem in the northern Rocky Mountains, and similar studies have been in progress for 3 years in the southern Appalachians. Thus far, the most important variation isolated in these studies is that of ground wind velocity with elevation and aspect.

An example will indicate to fire specialists how the findings of this study may eventually be applied, at the same time indicating deficiencies in present knowledge and a direction for future work.

A small portion of the Pisgah Ranger District of the Pisgah National Forest, in western North Carolina, has been used for this illustration. For May 6 and November 6, near the peak of the spring and fall fire seasons, a typical set of conditions has been assumed; namely, air temperature of 70° F., relative humidity of 40 percent, no wind at the litter surface, and the hour of 2 p. m., when the moisture content of light fuels is likely to be close to the equilibrium point. Usually, on those dates, a typical hardwood forest at the average elevation of the Pisgah district, about 4,000 feet, is leafless and a maximum of sunlight penetrates the stand and reaches the fuels of the forest floor.

To illustrate in detail the variations in fuel moisture equilibria associated with topography, due to unequal insolation, lines passing through points of equal surface fuel moisture equilibria as determined according to the findings of this study have been superimposed on an enlarged contour map of this area, which is roughly 2½ miles square, for May 6 and November 6 (fig. 14). The variation brought out emphasizes the problem confronting one who must locate fire-danger stations to sample "representative" conditions of fuel moisture. Knowledge of this variation, however, should help him choose locations that meet the specifications set up. The spread in equilibrium fuel moisture on November 6 is 5 percent, a difference particularly significant in such a low range of fuel moisture as that represented here. On May 6 fuel moistures are lower and there is less difference between north- and south-facing slopes, because the sun is higher and its rays are more effective.

Table 5, showing the relative portions of the area on which equilibrium surface fuel moisture content was theoretically of given classes on the two dates, emphasizes the significance of the seasonal differences brought out in figure 14. In the southern Appalachian system of danger rating, fuel moisture of less than 4 percent is classed as critical. In May, equilibrium moisture content falls in this extreme class on 76 percent of the area used in the illustration; in November, under exactly the same atmospheric conditions it does so on only 9 percent. In other words, in November it is likely that fewer fires will start and those that start will spread more slowly and be easier to control on much more of the area than in May, even though all atmospheric conditions are the same for both dates.

Basic information such as that used to construct figure 14 can be tabulated as in table 6 to gain an appreciation of the range in equilibrium fuel moistures that may be expected in mountainous country and to facilitate its use by field men.

TABLE 5.—*Fuel moisture classification of sample area for May 6 and November 6*

Equilibrium fuel moisture content (percent)	Proportion of total area		Equilibrium fuel moisture content (percent)	Proportion of total area	
	May 6	November 6		May 6	November 6
	Percent	*Percent*		*Percent*	*Percent*
Less than 3	53	0	Less than 7		88
Less than 4	76	9	Less than 8		97
Less than 5	96	49	Less than 9		100
Less than 6	100	70			

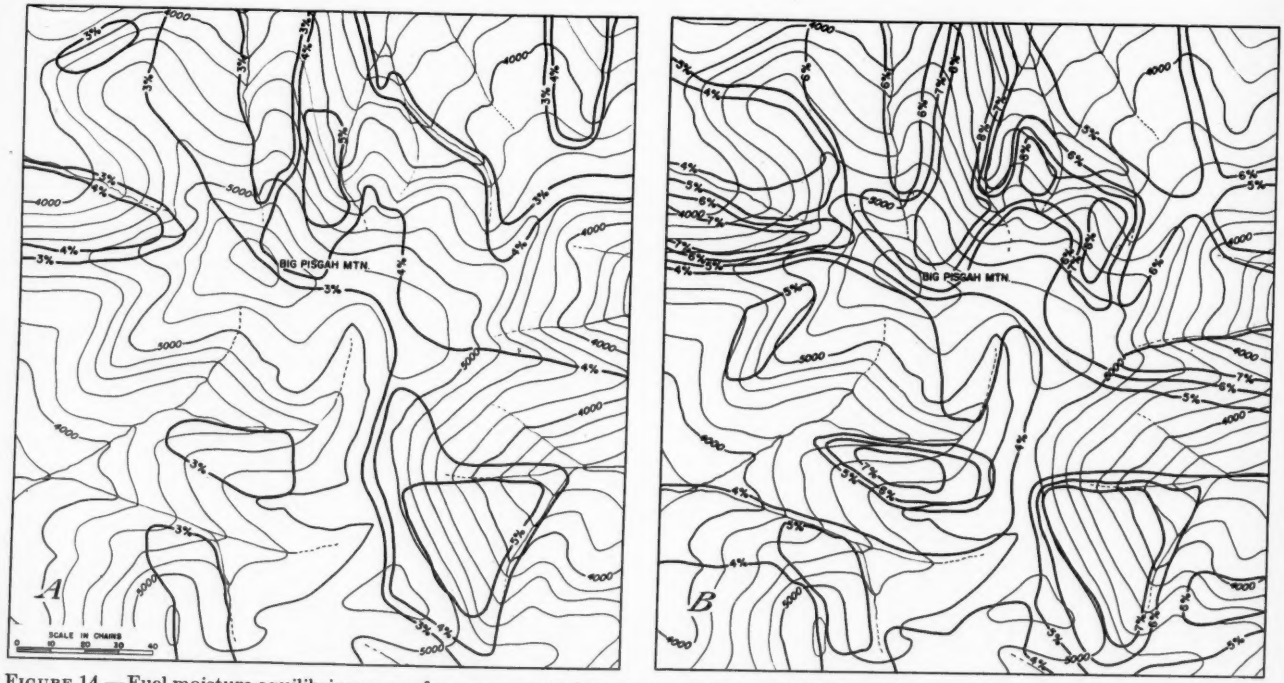

FIGURE 14.—Fuel moisture equilibrium maps for a representative portion of the Pisgah National Forest, N. C.: *A*, May 6; *B*, November 6.

TABLE 6.—*Fuel moisture equilibria for sample area, by aspect, slope, and wind class, when air temperature is 70° F., relative humidity is 40 percent, and hour is 2 p. m.*

MAY 6

Aspect[1]	Fuel moisture by steepness of slope (percent) and velocity of wind									
	20		40		60		80		100	
	0 mph	3 mph	0 mph	3 mph	0 mph	3 mph	0 mph	3 mph	0 mph	3 mph
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
N	3	5	3	5	4	6	4	6	4	6
NE	3	5	4	5	5	6	5	6	6	7
E	3	5	3	5	5	6	5	6	5	7
SE	3	5	3	5	4	5	4	5	4	6
S	2	4	2	5	3	5	3	5	3	5
SW	2	4	2	4	2	4	2	4	2	4
W	2	4	2	4	2	4	2	4	2	4
NW	3	5	3	5	3	5	3	5	3	5
NOVEMBER 6										
N	5	7	6	7	7	8	8	8	8	8
NE	5	7	6	7	8	8	8	8	8	8
E	5	6	6	7	6	7	7	8	8	8
SE	4	6	4	6	4	6	4	6	5	6
S	4	6	4	6	3	5	3	5	3	5
SW	4	6	3	5	3	5	3	5	4	5
W	4	6	4	6	4	6	4	6	4	6
NW	5	6	5	6	5	6	6	7	6	7

[1] For flats, the fuel moisture percent is as follows: Wind of 0 mph, 2 percent on May 6, 4 percent on Nov. 6; wind of 3 mph, 5 percent on May 6, 6 percent on Nov. 6.

Obviously, one condition that complicates the application of the findings regarding equilibrium fuel moisture relations to a heterogeneous forest area is the variation in air temperature, air humidity, and wind from one locality to another. Until more is known about such differences, much of the significance of the relation of radiation to equilibrium fuel moisture must lie in the basic theory developed rather than in everyday application by fire-control administrators. Nevertheless, the importance of determining the variations of atmospheric factors with topography becomes more evident when the potential differences in actual rate of spread of fires resulting from the extremes of fuel moisture noted in figure 14 are estimated. The rate-of-spread figures vary not only with atmospheric factors, but also with steepness of slope, fuel type, and perhaps other factors. On the average slope, on a calm day, and in leaf litter typical of the southern Appalachians, fires burning in fuel with 4 percent moisture would increase their perimeter about 4 or 5 chains per hour faster than fire burning in fuel with 8 percent moisture. All other things being equal, a dispatcher recognizing such a difference in fuel moisture would have to send two or three more men to a fire in the drier fuels than to a similar fire in the more moist fuels, if control were to be accomplished in the average length of time.

It must be emphasized that several other considerations influence manpower requirements for fire control to a much greater extent than 4- or 5-percent differences in fuel moisture. It must be remembered also that only for the very light surface fuels is moisture content frequently near equilibrium with that of their surroundings; therefore, the data presented here do not apply to fuels heavier than hardwood leaves, dead grass, and surface layers of pine needles.

SUMMARY

Forest fire-danger rating systems, now in use in all forest regions of the United States, are based chiefly on measurement of wind and of fuel moisture. While many workers have investigated atmospheric and related elements that control fuel moisture, little research has been done on solar radiation and its influence on fuel moisture equilibria and rates of drying. With a view to contributing to the refinement of fire-danger rating systems and application of the ratings, a study of solar radiation and fuel moisture was begun in the southern Appalachians in 1938.

A method has been developed whereby radiation intensity can be determined for any season of year, hour of day, slope, and aspect. Examples are given showing the widely different radiation intensities that are to be expected under different combinations of these factors even though atmospheric conditions are the same. The relation of solar radiation intensity to surface fuel moisture equilibria and, to a lesser extent, its relation to rates of drying have been established on the basis of theory and of data obtained by use of an "artificial sun" apparatus, a specially constructed weather synthesizer. This apparatus permits both field and laboratory observation of moisture equilibria and rates of drying under various combinations of radiation, wind, and humidity. Formulae have been developed so that for any combination of air temperature, relative humidity, and wind velocity, equilibrium moisture content of forest litter can be derived for any season, slope, and aspect. These formulae can be used universally, provided radiation intensities are adjusted for latitude.

The influence of wind on fuel drying is emphasized. In bright sunlight, contrary to popular belief, wind maintains levels of fuel moisture higher than those in calm air. The reason is that for fuels in the sun the wind's cooling action more than offsets its drying action. This is important in some regions where fuels are fully exposed to sunlight during the fire season.

Fuel moisture equilibrium maps are presented showing variations with season, aspect, and slope that result from variations in radiation intensity alone. A table is presented showing differences in drying rates caused by differences in radiation.

LITERATURE CITED

(1) Breed, C. B., and Hosmer, G. L.
1908. The principles and practice of surveying. v. ii. 432 pp., illus. New York.

(2) Brown, A. A., and Davis, W. S.
1939. A fire danger meter for the Rocky Mountain region. Jour. Forestry 37: 552–558, illus.

(3) Byram, G. M.
1940. Sun and wind and fuel moisture. Jour. Forestry 38: 639–640, illus.

(4) Curry, J. R., Gray, L. G., and Funk, I. C.
1940. Forest fire-danger rating and its application in California. Jour. Forestry 38: 855–866, illus.

(5) Forsythe, W. E.
1937. Measurement of radiant energy. 452 pp., illus. New York.

(6) Gast, P. R., and Stickel, P. W.
1929. Solar radiation and relative humidity in relation to duff moisture and forest fire hazard. U. S. Monthly Weather Rev. 57: 466–468, illus.

(7) GISBORNE, H. T.
1933. DEADWOOD LYING ON DUFF DRIER THAN IN AIR. Jour. Forestry 31: 979–980.
(8) ———
1936. THE PRINCIPLES OF MEASURING FOREST FIRE DANGER. Jour. Forestry 34: 786–793, illus.
(9) ———
1936. MEASURING FIRE WEATHER AND FOREST INFLAMMABILITY. U. S. Dept. Agr. Cir. 398, 59 pp., illus.
(10) HAWLEY, L. F.
1931. WOOD-LIQUID RELATIONS. U. S. Dept. Agr. Tech. Bul. 248, 35 pp., illus.
(11) HAYES, G. L.
1941. INFLUENCE OF ALTITUDE AND ASPECT ON DAILY VARIATIONS IN FACTORS OF FOREST-FIRE DANGER. U. S. Dept. Agr. Cir. 591, 38 pp., illus.
(12) JEMISON, G. M.
1935. INFLUENCE OF WEATHER FACTORS ON MOISTURE CONTENT OF LIGHT FUELS IN FORESTS OF THE NORTHERN ROCKY MOUNTAINS. Jour. Agr. Res. 51: 885–906, illus.
(13) MATTHEWS, D. N.
1937. RATING FIRE DANGER. Timberman 38 (6): 16–17, illus.
(14) MITCHELL, M. A.
1929. FOREST FIRE HAZARD . . . Wis. Agr. Expt. Sta. Res. Bul. 91, 26 pp., illus.
(15) STICKEL, P. W.
1931. THE MEASUREMENT AND INTERPRETATION OF FOREST FIRE-WEATHER IN THE WESTERN ADIRONDACKS. N. Y. State Col. Forestry, Syracuse Univ., Tech. Pub. 34, 115 pp., illus.

U. S. GOVERNMENT PRINTING OFFICE: 1943